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ABSTRACT

This course in electromechanical devices is one of 16 courses in the Energy Technology Series developed for an Energy Conservation-and-Use Technology curriculum. Intended for use in two-year postsecondary institutions to prepare technicians for employment, the courses are also useful in industry for updating employees in company-sponsored training programs. Comprised of seven modules, the course is designed to provide a working knowledge of control elements in electrical circuits, transformers, motors, and generators. Topics presented include switches, circuit breakers, relays, fuses, transformers, d.c. and a.c. motors, and generators. Written by a technical expert and approved by industry representatives, each module contains the following elements: introduction, prerequisites, objectives, subject matter, exercises, laboratory materials, laboratory procedures (experiment section for hands-on portion), data tables (included in most basic courses to help students learn to collect or organize data), references, and glossary. Module titles are Electromechanical Devices--An Introduction, Control Elements in Electrical Circuits, Transformers, Generators and Alternators, D.C. Motors and Controls, A.C. Motors and Controls, and Synchromechanisms. (KLB)

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ED210507

ELECTROMECHANICAL

DEVICES

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT
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PREFACE

ABOUT ENERGY TECHNOLOGY MODULES

The modules were developed by CORD for use in two-year postsecondary technical institutions to prepare technicians for employment and are useful in industry for updating employees in company-sponsored training programs. The principles, techniques, and skills taught in the modules, based on tasks that energy technicians perform, were obtained from a nationwide advisory committee of employers of energy technicians. Each module was written by a technician expert and approved by representatives from industry.

A module contains the following elements:

Introduction, which identifies the topic and often includes a rationale for studying the material.

Prerequisites, which identify the material a student should be familiar with before studying the module.

Objectives, which clearly identify what the student is expected to know for satisfactory module completion. The objectives, stated in terms of action-oriented behaviors, include such action words as operate, measure, calculate, identify, and define, rather than words with many interpretations such as know, understand, learn, and appreciate.

Subject Matter, which presents the background theory and techniques supportive to the objectives of the module. Subject matter is written with the technical student in mind.

Exercises, which provide practical problems to which the student can apply this new knowledge.

Laboratory Materials, which identify the equipment required to complete the laboratory procedure.

Laboratory Procedures, which is the experiment section, or "hands-on" portion, of the module (including step-by-step instruction) designed to reinforce student learning.

Data Tables, which are included in most modules for the first year (or basic) courses to help the student learn how to collect and organize data.

References, which are included as suggestions for supplementary reading/viewing for the student.

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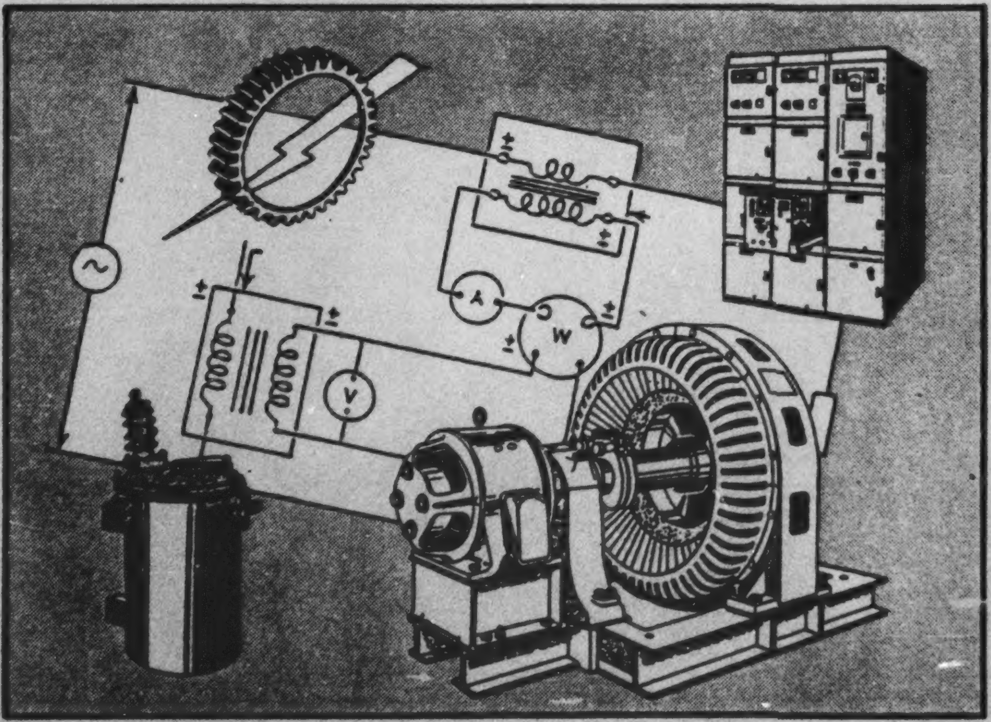
ENERGY TECHNOLOGY
CONSERVATION AND USE

ELECTROMECHANICAL DEVICES



MODULE EM-01

ELECTROMECHANICAL DEVICES — AN INTRODUCTION

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

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INTRODUCTION

An electromechanical energy conversion device is a link between an electrical system and a mechanical system. By appropriately coupling the two systems, the device transfers energy from one system to the other. An electric generator converts mechanical input energy to electrical output energy; an electric motor converts electrical input energy to mechanical output energy. The coupling of the electrical and mechanical systems is achieved through magnetic fields. Current flow through an electrical conductor in a magnetic field produces the mechanical force that turns a motor. In a generator, an electrical potential is produced across a conductor by applying a mechanical force to move it through a magnetic field.

This module introduces the conversion of energy by electromechanical devices and includes a discussion on the magnetic forces and fields that are the bases of operation of such devices. Topics discussed include origin and characteristics of magnetic forces and fields, electromagnets, and basic principles of motors and generators. In the laboratory, the student will examine the characteristics of the magnetic fields of permanent magnets and electromagnets.

PREREQUISITES

The student should have completed a course in d.c. and a.c. circuit analyses.

OBJECTIVES

Upon completion of this module, the student should be able to:

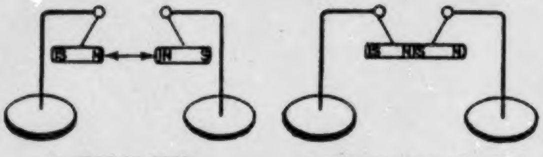
1. State two rules of magnetic attraction and repulsion.
2. Explain the concepts of magnetic lines of force and of magnetic fields.
3. Draw diagrams showing the magnetic field lines of the following:
    a. Field of a bar magnet
    b. Field between the north pole of one magnet and the south pole of another

   - c. Field between the north poles of two magnets
   - d. Field around a long, straight, current-carrying conductor
   - e. Field of a current-carrying conductor loop
   - f. Field of a solenoid

4. Explain the concept of magnetic domains in magnetic materials and how this concept accounts for each of the following:
   - a. Permanent magnets
   - b. Magnetic induction
5. List the four factors affecting the magnetic strength of an electromagnet and explain how variations in each affect the magnetic field.
6. Explain hysteresis.
7. Draw and label a diagram showing the resulting magnetic field lines and force when an electron travels in a direction into the page through a vertical magnetic field.
8. Use the right-hand rule to determine the following:
   - a. The direction of the force on the electrons in a conductor forced to move through a magnetic field
   - b. The direction of the force on a current-carrying conductor in a magnetic field
9. Given a diagram of a loop of wire rotating in a magnetic field, determine the direction of loop rotation.

MAGNETIC FORCES AND FIELDS

The operation of all electromechanical devices is based on the forces of attraction and repulsion that exist between two magnetic fields. These forces can be demonstrated by suspending two magnets from strings, as shown in Figure 1. If the magnets are positioned so the north poles of each are near one another (Figure 1a), the magnets will repel. The same is true if the two south poles are brought together. If the north pole of one magnet is placed near the south pole of the other (Figure 1b), the magnets will attract. Therefore, the basic rules of direction of magnetic force are as follows:



a. LIKE POLES REPEL.

b. UNLIKE POLES ATTRACT.

Figure 1. Demonstrations of the First Two Laws of Magnetism.

- Like poles repel.
- Unlike poles attract.

The magnitude of the magnetic force is given mathematically by the following equation:

$$F = \frac{\mu M_1 M_2}{d^2} \qquad \text{Equation 1}$$

where: F = Magnetic force.
M_1 = Strength of first magnet.
M_2 = Strength of second magnet.
d = Distance between magnets.
μ = Permeability of material between magnets.

The magnetic force can be increased by increasing the strength of either magnet or by bringing the magnets closer together. The magnetic permeability of a material is the property that permits easy conduction of magnetic lines of force through the material. Iron, for example, will conduct magnetic force lines much better than air.

The concept of a magnetic line of force is illustrated in Figure 2. The direction of the magnetic force at any point is defined as "the direction of

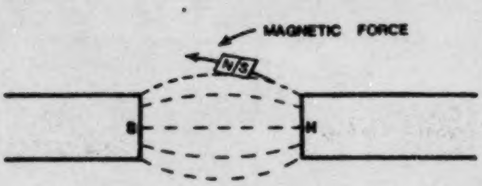


Figure 2. Magnetic Lines of Force.

the force on a tiny north pole placed at that point." (This is indicated by the solid arrow in Figure 2.) Although it is not possible to have a north pole without a south pole, the south pole is ignored for the purpose of defining the direction of the magnetic field. A magnetic line of force is a line that would be followed by the tiny north pole if it were free to move. Magnetic lines of force are shown as dotted lines in Figure 2. The direction of the line of force at any point in space is the same as the direction of the magnetic force on a north pole placed at that point. Thus, magnetic lines of force are always directed away from north poles and toward south poles.

Figure 3 shows some of the magnetic lines of force of a bar magnet. The pattern formed by these lines is called "the magnetic field of the magnet"; it indicates both the direction and the strength of the magnetic force on a small north pole located in the vicinity of the magnet. The strength of the field at any point is indicated by the density of field lines near that point.

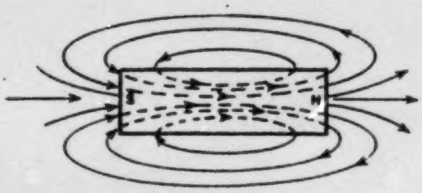
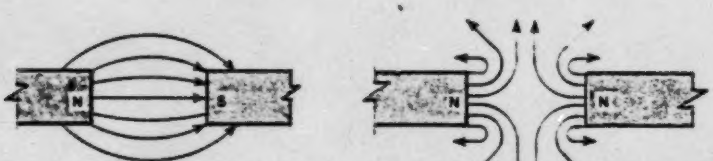


Figure 3. Magnetic Field of a Bar Magnet.

The magnetic lines do not actually begin at the north pole and end at the south pole. They are really closed loops that extend through the magnet, as indicated by the dotted lines in Figure 3.

Figure 4a shows the magnetic field that results when the north pole of one magnet is placed near the south pole of another. Figure 4b is the field of two north poles placed close together. The field produced by two south poles would have the same distribution of field lines but would be directed in the opposite direction.



a. NORTH POLE PLACED NEAR SOUTH POLE

b. NORTH POLE PLACED NEAR NORTH POLE

Figure 4. Magnetic Fields of Two Magnets.

The names of the magnetic poles were derived from the early use of magnetized needles as compasses. In these compasses, the end of the needle that pointed north was naturally called the "north pole," or the "north-seeking pole." The end that pointed south was the "south pole." However, since like poles repel and unlike poles attract, the "north" pole of the compass must point toward a "south" magnetic pole. Figure 5 illustrates the earth's magnetic field and shows that the magnetic pole located in the position called "north" is actually a "south" magnetic pole.

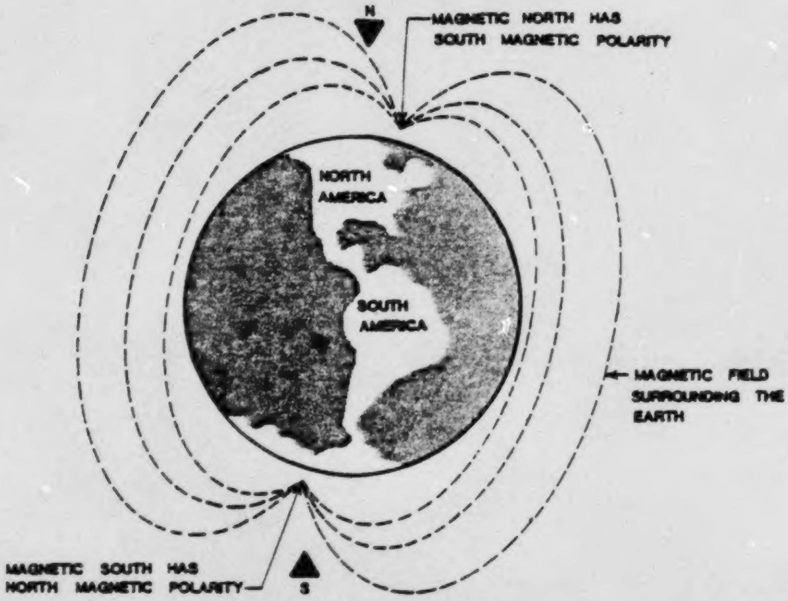

N
MAGNETIC NORTH HAS SOUTH MAGNETIC POLARITY
NORTH AMERICA
SOUTH AMERICA
MAGNETIC FIELD SURROUNDING THE EARTH
MAGNETIC SOUTH HAS NORTH MAGNETIC POLARITY
S

Figure 5. The Earth's Magnetic Field.

THE ORIGIN OF MAGNETISM

A magnetic field is produced by a moving electrical charge. A moving charge is the only thing that can produce a magnetic field and the only thing that can be affected by one.

Figure 6 shows an electron moving to the right in a straight line and the magnetic field it produces. The direction of the field is in a circle around the electron. The direction can be determined by grasping the electron in the left hand with the thumb extended in the direction of motion. The fingers of the left hand will then curl in the direction of the magnetic field.

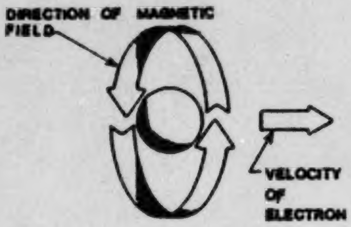


Figure 6. Magnetic Field of a Moving Electron.

This field is a closed loop and has no poles. The strength of the field produced depends upon the magnitude of the moving charge and the speed at which it travels. Stationary charges do not produce magnetic fields.

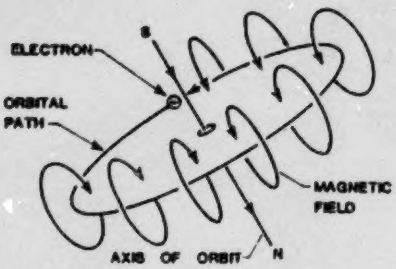


Figure 7. Magnetic Field of Orbiting Electron.

Magnetic fields produce poles only when the charge producing the field moves along a closed loop. Figure 7 shows the magnetic field produced by an electron as it orbits around the nucleus of an atom. The field along the axis of the orbit is the strongest and always points in the same direction.

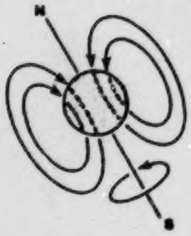


Figure 8. Magnetic Field of Spinning Electron.

Electrons can also spin about their own axis, producing a magnetic field, as shown in Figure 8. This magnetic field also exhibits a north pole and a south pole. Spinning protons in the atomic nucleus have similar magnetic fields.

An atom consists of spinning electrons that orbit around a nucleus containing spinning protons. Thus, every atom contains several magnetic fields. The total of all these fields is the magnetic field of the atom. The magnetic fields of most atoms are small, but, in ferromagnetic materials, the individual magnetic fields within each atom align to produce a strong magnetic field. Each atom is a tiny magnet.

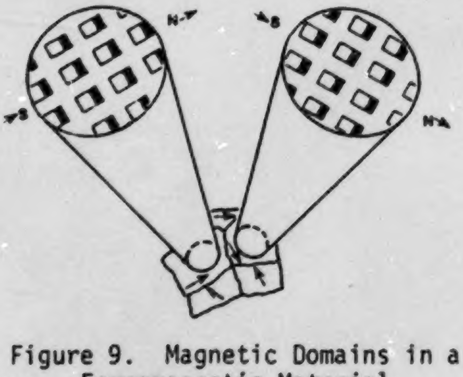
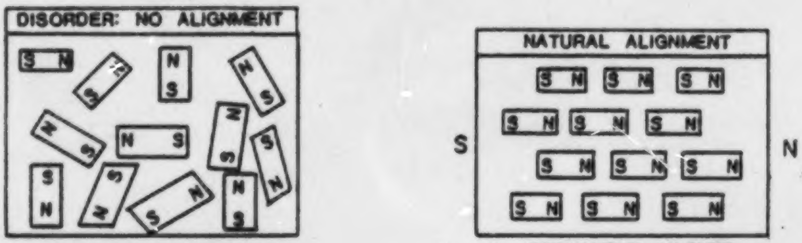


Figure 9. Magnetic Domains in a Ferromagnetic Material.

The magnetic field of each atom tends to align itself with its neighbors to form magnetic domains, as shown in Figure 9. Each domain consists of large numbers of atoms with their magnetic fields pointing in the same direction. Magnetic materials contain many small domains. About ten million magnetic domains are contained in a cubic centimeter of iron. Each domain can be thought of as a small magnet within the material.

Figure 10a shows the orientation of the domain magnets in an unmagnetized material. The magnetic fields of the randomly oriented magnetic domains cancel; therefore, the material exhibits no net magnetic field. In Figure 10b, the domain magnets have been aligned to form the net magnetic field of a permanent magnet.

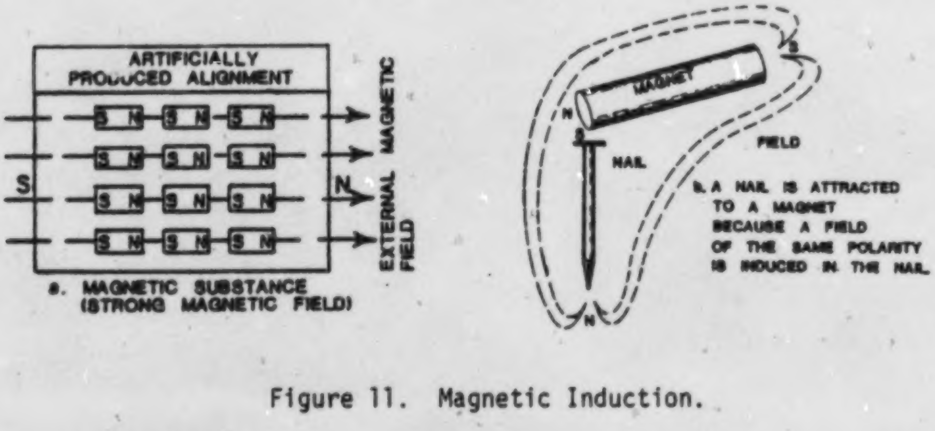

DISORDER: NO ALIGNMENT
NATURAL ALIGNMENT
S
N

a. UNMAGNETIZED SUBSTANCE (NO MAGNETIC FIELD)

b. PERMANENT MAGNET (STRONG MAGNETIC FIELD)

Figure 10. Magnetic Domains in Materials.

The domain theory of magnetism also explains how a magnet can attract a piece of ferromagnetic material that is not magnetized. Figure 11a shows the alignment of the domain magnets with an externally-produced magnetic field. This occurs any time the material is subjected to a strong magnetic field. The magnet in Figure 11b attracts the nail because its field has induced a magnetic field in the nail. This process is called "magnetic induction."


ARTIFICIALLY PRODUCED ALIGNMENT
S
N
EXTERNAL MAGNETIC FIELD
MAGNET
N
S
FIELD
NAIL
N

a. MAGNETIC SUBSTANCE (STRONG MAGNETIC FIELD)

b. A NAIL IS ATTRACTED TO A MAGNET BECAUSE A FIELD OF THE SAME POLARITY IS INDUCED IN THE NAIL

Figure 11. Magnetic Induction.

When the bar magnet is removed, many of the magnetic domains in the iron nail will return to a random orientation, and the magnetic field of the nail will decrease greatly. The alignment of a few of the domains will be permanently changed to the direction of the applied field. This is called "residual magnetism" and will result in a small magnetic field in the nail even after the bar magnet is removed.

However, this residual field can be removed in the following ways: If the magnetized nail is heated, the increased molecular motion will return all the domains to a random orientation; or if the nail is subjected to a strong mechanical shock, such as being dropped on a hard surface, the mechanical energy will produce a random orientation of the magnetic domains. Thus, permanent magnets should be protected from both high temperature and mechanical shocks.

The residual field can also be removed by applying a magnetic field in the opposite direction of the field originally induced in the material. Figure 12 shows how the magnetic field in a material varies as the applied magnetic field is changed. Vertical distance represents the strength and direction of the externally-applied field; horizontal distance represents the strength and direction of the field inside the material.

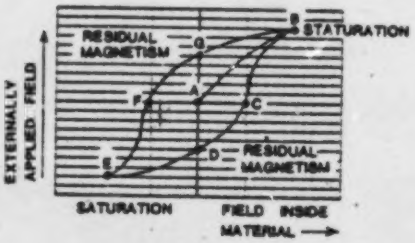


Figure 12. Hysteresis Loop of a Magnetic Material.

At point A, the magnetic field in the material and the applied field are both zero. At point B, an external field has been applied, and the internal field has increased to the maximum possible value for the value of the applied field. This is called the "saturation point." At point C, the applied field has been returned to zero, but, because of residual magnetism, the internal field has a nonzero value in the direction of the original applied field. At point D, an external field has been applied in the opposite direction to return the internal field to zero. At point E, a greater applied field has reversed the direction of the internal field. Another reversal of the external field will return the internal field to point B along the path containing points F and G.

This closed loop is called the "hysteresis loop" of the material. The area enclosed by the loop represents the energy necessary to change the directions of the magnetic domains in the material. This energy appears in the material as heat. Hysteresis losses are an important consideration in alternating magnetic systems. The materials in such systems are chosen to reduce hysteresis losses.

MAGNETIC FIELDS OF ELECTRIC CURRENTS

Magnetic fields are always the result of moving electrical charges. Figure 6 showed the field produced by a single charged particle in motion. Figure 13 illustrates the similar fields produced by a current flowing in a wire. The magnetic field of a current-carrying conductor is the sum of the individual fields of all the charges moving through the conductor. The direction of the field can be determined by grasping the conductor with the left hand with the thumb extended in the direction of electron flow. The fingers will then curve in the direction of the circular field.

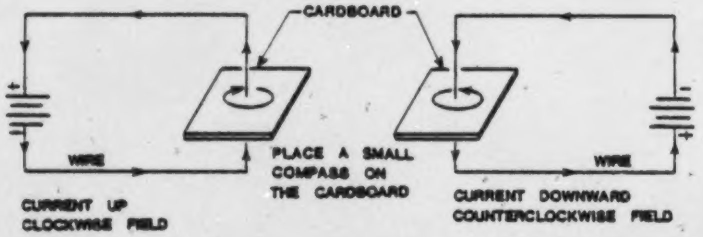

CARDBOARD
WIRE
PLACE A SMALL COMPASS ON THE CARDBOARD
WIRE
CURRENT UP
CLOCKWISE FIELD
CURRENT DOWNWARD
COUNTERCLOCKWISE FIELD

Figure 13. Magnetic Fields Produced by Current Flowing in a Wire.

Figure 14 shows another view of the magnetic field of current-carrying conductors. The dot represents the tip of an arrow emerging from the page to indicate current out of the page. The cross represents the feathered end of an arrow entering the page to indicate a current entering the page.

The magnetic field produced by a long, straight conductor is a circular field around that conductor and

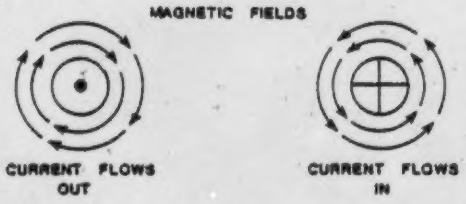
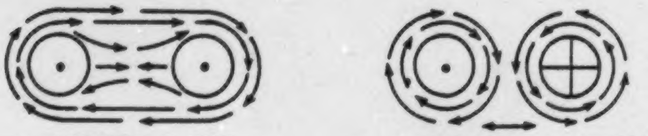

MAGNETIC FIELDS
CURRENT FLOWS OUT
CURRENT FLOWS IN

Figure 14. Magnetic Field of Current-Carrying Conductors.

has maximum strength near the conductor. Like the field of a single moving charge, it has no identifiable poles.

Figure 15 shows what happens if two straight conductors are brought close to one another. If the direction of the currents is the same (Figure 15a), the magnetic fields merge to form a single field surrounding both conductors, and the moving charges in the conductors are attracted toward one another. If the currents flow in opposite directions (Figure 15b), the two fields oppose one another between the wires, and the moving charges in the conductors repel one another. These magnetic forces of attraction and repulsion between current-carrying conductors are the bases of all electromechanical energy converters.


a. CURRENTS IN SAME DIRECTION (FIELD ATTRACT)

b. CURRENTS IN OPPOSITE DIRECTIONS (FIELD REPEL)

Figure 15. Attractive or Repulsive Forces Between Magnetic Fields.

Figure 7 illustrated how an electron moving in a circular orbit produces the magnetic poles of an atom. Figure 16 illustrates the same principle applied to a loop of wire. Magnetic poles are created only when electrical charges move around closed loops.

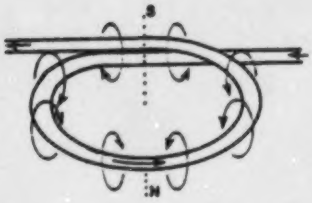


Figure 16. Magnetic Field of a Current-Carrying Loop.

Several loops of wire can be wound close together to form a coil. Figure 17 shows current flow and magnetic fields in a coil. The individual magnetic fields of all the loops of wire add to produce a much stronger field.

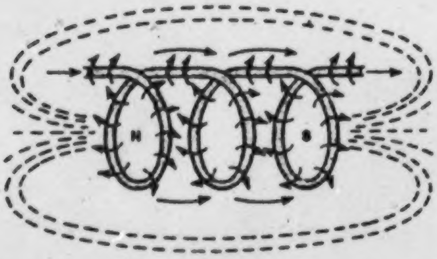


Figure 17. Current Flow and Magnetic Fields in a Coil.

When the coil is wound around a cylinder of magnetic material, called a "core," an electromagnet is formed. Figure 18 shows such an electromagnet. The magnetic field of the coil induces a field in the core. The two fields added together produce a total field that has far greater strength than that of the coil alone. The strength of an electromagnet is dependent upon the following factors:

- Number of turns of wire in the coil
- Current flowing through the coil
- Kind of core material
- Ratio of coil length to its diameter

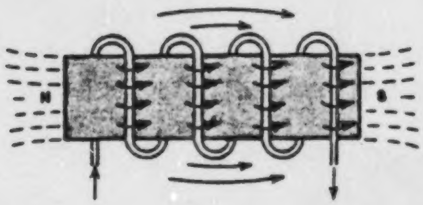
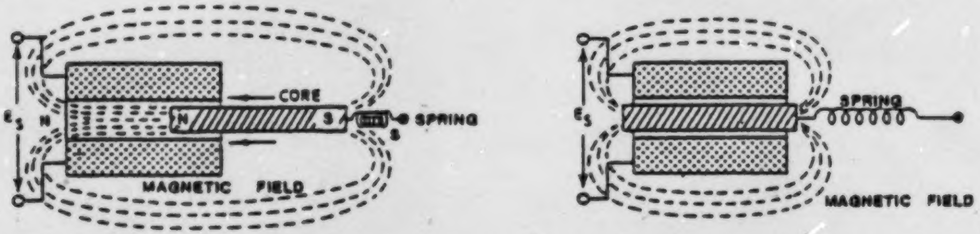


Figure 18. An Electromagnet.

The field intensity of a coil will remain uniform throughout the cross section of the coil if the length of the coil is 10 times or more greater than the coil diameter.

A solenoid is formed if the coil of an electromagnet is wound on a hollow form and the core is free to slide within the form. Figure 19 illustrates the operation of such a solenoid. The core is initially at rest with only one end inside the coil. When a current is established in the coil, a magnetic field appears within the core. The end of the core inside the coil is in a much more intense magnetic field than the end outside the coil; therefore, the magnetic forces on it are the greatest. Thus, the magnetic field starts to suck the core into the coil (Figure 19a). The core will be forced to the center of the coil so that the length of the magnetic lines between the poles of the coil is at a minimum (Figure 19b). When the current is turned off, a spring returns the core to its original position.



a. b.

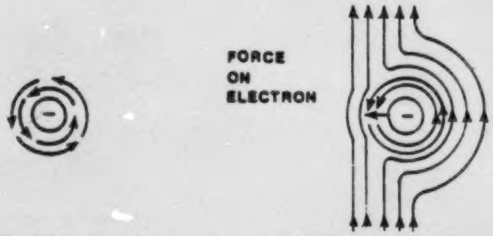
Figure 19. Operation of a Solenoid.

The solenoid is a common method of converting electrical energy to electromagnetism and then to mechanical movement. A rod attached to the core can be linked to levers, gears, or switches to perform a variety of operations.

Such a device is used in automobiles to move the pinion gear on the starter to mesh with the flywheel gear. Electrical relays consist of a solenoid that operates a switch or a series of switches.

FORCES ON CHARGED PARTICLES MOVING THROUGH MAGNETIC FIELDS

Figure 20a shows the magnetic field of an electron moving into the page. The direction of this field can be verified by grasping the electron in the left hand with the thumb of that hand extended in the direction of electron motion (into page). The fingers will curl in the counterclockwise direction of the magnetic field.



a.MAGNETIC FIELD OF ELECTRON MOVING INTO PAGE

b.MAGNETIC FIELD OF ELECTRON MOVING INTO PAGE IN A VERTICAL MAGNETIC FIELD

Figure 20. Magnetic Force on an Electron Moving Through a Magnetic Field.

Figure 20b shows the same electron moving into the page through a vertical magnetic field with an upward direction.

On the right side of the electron, the external field and the field of the electron add to produce a stronger field. On the left side, the two fields are in different directions and add to produce a weakened field. The electron field is strongest near the electron to give a net downward field. At great distances, the external field is stronger to give a net upward field. At some point between, the two fields add to zero.

The electron experiences a magnetic force in the direction of the weakened point in the magnetic field and away from the strongest point of the field. The direction of this force is always perpendicular to both the direction of motion of the electron and the applied magnetic field. As in all cases, the magnetic forces arise because the magnetic field lines always "contract" to produce the shortest possible closed path.

The direction of the force on an electron moving through a magnetic field is given by the right-hand rule illustrated in Figure 21. The thumb, forefinger, and middle finger of the right hand are held at right angles to one another. The Forefinger points in the direction of the Field. The Middle finger points in the direction of Movement of the electron. The Thumb points in the direction of the Thrust (the magnetic force on the electron). The forces described by the right-hand rule are responsible for directing the electron beam in a television picture tube to the proper point on the screen and are the bases of all electric motors and generators.

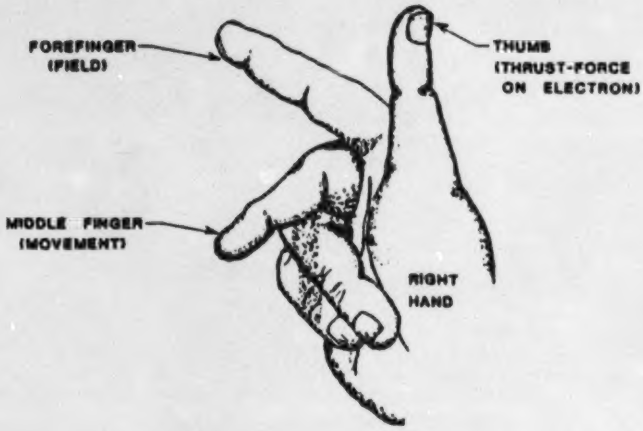


Figure 21. The Right-Hand Rule.

GENERATOR ACTION

Figure 22 shows how the magnetic forces on moving electrons produce voltage in an electric generator. In Figure 21a, an electrical conductor moves upward through a magnetic field directed to the right. An application of the right-hand rule reveals that the electrons in the conductor experience magnetic forces directed along the conductor from end A toward end B. Electrons that are free to move within the conductor flow away from A toward B. The result is an induced voltage across the conductor with A positive and B negative.

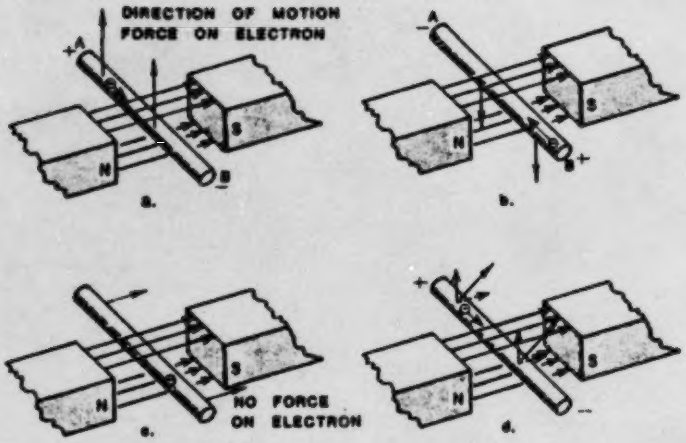


Figure 22. Generator Action.

In Figure 22b, the direction of motion of the conductor has been changed to a downward motion. This also reverses the force on the electrons, producing a positive electrical potential at B and a negative potential at A.

In Figure 22c, the conductor moves in the direction of the external magnetic field. In this case, the magnetic field lines of the moving electrons spiral around the external field lines but do not oppose the field. The net result is as follows: no force on the electrons and no induced voltage.

In Figure 22d, the conductor moves at an angle to the magnetic field. In this case, the component of the motion along the field lines makes no contribution to the induced voltage. Only the component of the motion perpendicular to the external magnetic field induces a voltage in the conductor. The voltage across the conductor depends upon the following factors:

- Strength of the magnetic field
- Length of the conductor
- Speed at which the conductor moves through the field
- Angle between the conductor motion and the field direction

The application of magnetic forces to convert mechanical energy to electrical energy in a d.c. generator is illustrated in Figure 23. The generator in this diagram consists of a single square loop of wire that rotates in a fixed magnetic field. Each end of the wire loop is connected to one-half of a split-ring conductor. Brushes resting on the split ring connect the rotating loop to an external electric circuit. The split ring and brush arrangement is called a "commutator."

In Figure 23a, the coil is just rotating past the vertical position. Wire segment A is moving to the left, and wire segment B is moving to the right. At this instant, both conductor segments are moving in the direction of the applied magnetic field. This produces no forces on their electrons, and the voltage across the loop is zero.

In Figure 23b, the rotation has continued. Wire segment B now has a downward component in its velocity. Applying the right-hand rule shows a force on the electrons in that conductor in the direction indicated. Wire segment A is moving upward, causing a force on its electrons in the opposite direction. The voltages of the two segments add in series to produce the generator output voltage. Wire segment C also moves through the magnetic field, but the forces induced on its electrons are across the wire — not along it. Thus, it makes no contribution to the output voltage.

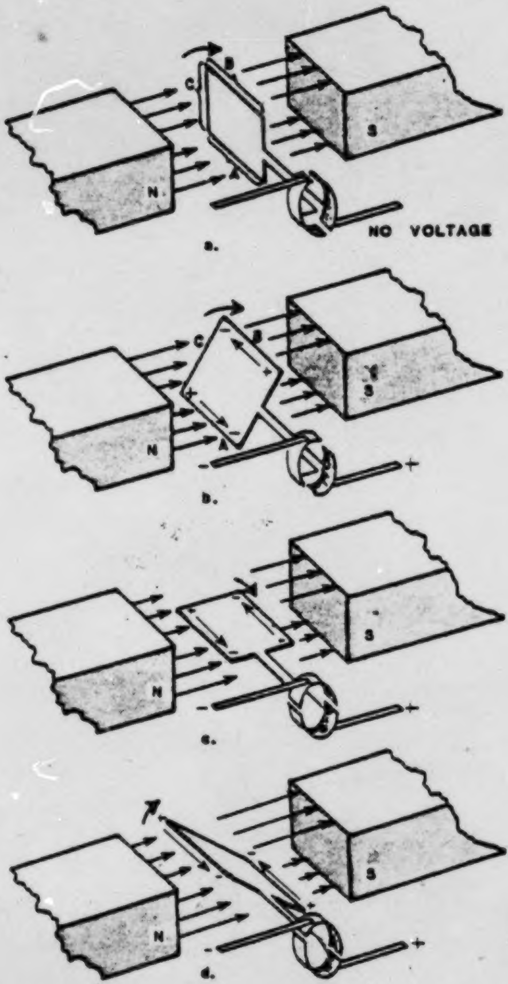


Figure 23. Operation of a d.c. Generator.

In Figure 23c, the coil has continued its rotation to be in a plane containing lines of magnetic force. At this point, the velocities of moving segments A and B are both perpendicular to the magnetic field direction. This produces the maximum output voltage.

In Figure 23d, rotation has continued, and the output voltage has dropped. When the coil reaches the vertical position again, as in Figure 23a, each brush will slip to the other segment of the split ring, and the process will be repeated.

The output waveform of this simple d.c. generator is shown in Figure 24. The points labeled a, b, c, and d correspond to the lettered drawings in Figure 23. The output voltage of the generator can be increased by increasing the strength of the magnetic field, the rotational rate, or the number of loops of wire used.

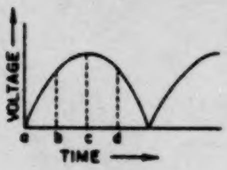


Figure 24. Output of a d.c. Generator.

Figure 25a shows a further improvement in generator design. This generator uses two coils of wire at right angles. Each is connected through the commutator to the output terminals of the generator only for that portion of the rotation that produces the maximum voltage. When the voltage begins to drop, that coil is removed from the circuit and replaced by the other coil in which the voltage is rising. Most electric motors and generators have multiple poles.

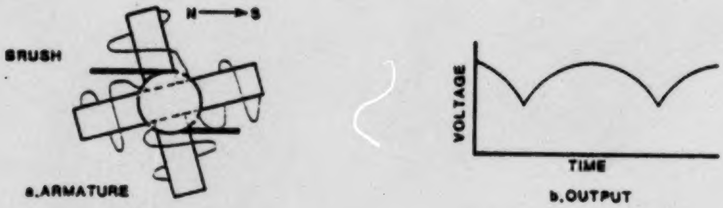


Figure 25. Generator with Four-Pole Armature.

Figure 26 shows the slip rings and output waveform of an a.c. electric generator, which is also called an "alternator" because it produces alternating current. In this case, each end of the rotating coil remains attached to the same output terminal. Since the direction of current flow in the coil changes twice for each revolution of the coil, the output current and voltage also change in direction.

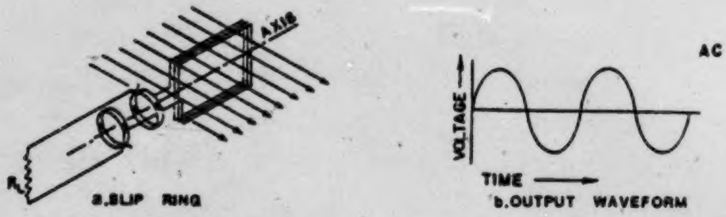


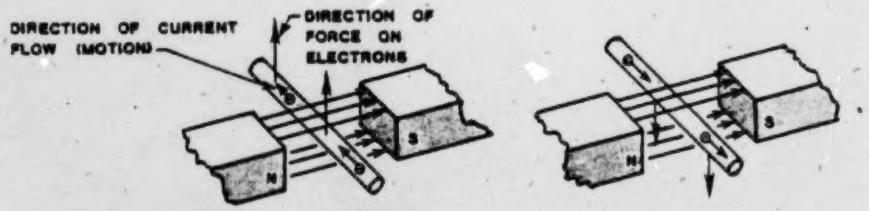
Figure 26. An a.c. Generator.

The magnetic fields for generators and alternators are usually provided by d.c. electric current flowing through coils of wire. In d.c. generators, the field coils are stationary, and the armature rotates inside the coils to produce the output voltage. In alternators, the magnetic field is rotated to create a current in stationary coils surrounding it. This is done because the current necessary to produce the magnetic field is small compared to the output current of the alternator. This smaller current passes through the brushes to establish the magnetic field while the larger output current of the stationary coils is connected directly to the output terminals. This arrangement reduces losses and increases brush life. All commercially-distributed electrical power produced in the United States is converted from mechanical rotational power by large alternators.

MOTOR ACTION

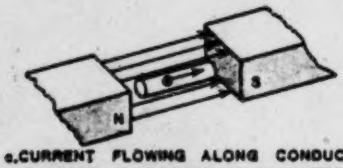
An electric generator converts mechanical energy to electrical energy. An electric motor does the reverse; it converts electrical energy to mechanical energy.

Figure 27 illustrates the forces on a current-carrying conductor in a magnetic field. Applying the right-hand rule to the electrons in the wire


DIRECTION OF CURRENT FLOW (MOTION)
DIRECTION OF FORCE ON ELECTRONS
N
S
N
S

a. UPWARD MAGNETIC FORCE ON ELECTRONS

b. REVERSING DIRECTION OF CURRENT REVERSES DIRECTION OF FORCE



c. CURRENT FLOWING ALONG CONDUCTOR IN SAME DIRECTION AS MAGNETIC FIELD

Figure 27. Forces on a Current-Carrying Conductor in a Magnetic Field.

in Figure 27a reveals an upward magnetic force on the electrons. Since these electrons cannot escape from the wire, they move upward and take the wire with them.

In Figure 27b, reversing the direction of the current in the conductor has reversed the direction of the force on the wire. Figure 27c shows current flowing along a conductor in the same direction as the magnetic field. In this case, there is no component of electron motion across the field lines, and no forces are produced.

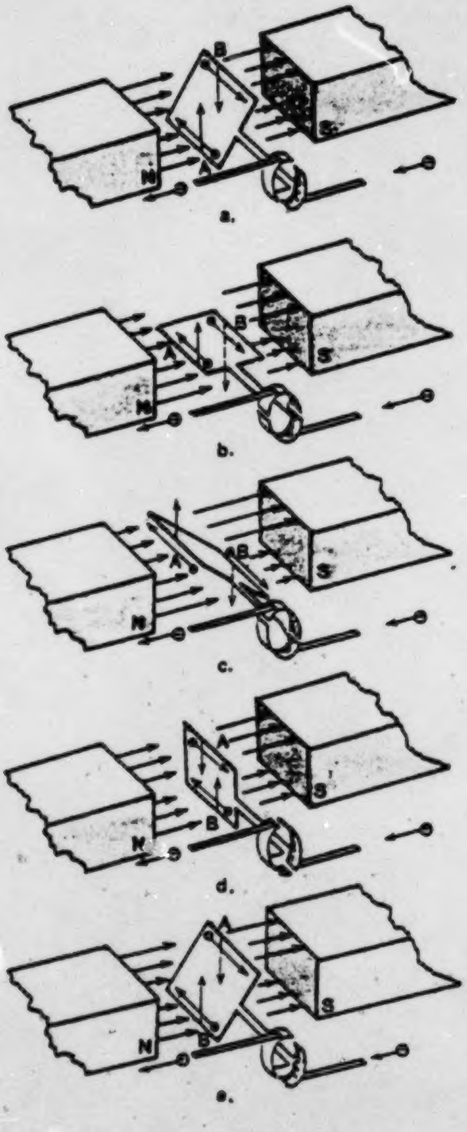


Figure 28. Operation of a d.c. Electric Motor.

Figure 28 shows the application of these principles to the conversion of electrical energy to mechanical energy in a d.c. electric motor. This is exactly the same device that acted as a d.c. generator in Figure 23.

In Figure 28a, a current flows through a loop of wire in a magnetic field. The current produces an upward force on wire segment A and a downward force on wire segment B. These forces act together to produce a torque that rotates the coil within the field. The force produced on wire segment C is along the axis of rotation of the motor and makes no contribution to the motor output torque.

In Figure 28b, the coil has rotated to lie in a plane parallel to the direction of the magnetic field. The forces on A and B remain the same, but, in this case, these forces act at a maximum distance from the axis of rotation to produce maximum motor torque. The coil continues to rotate through the position shown in Figure 28c with decreasing torque until it reaches a vertical position where the torque is zero. At this point, each of the brushes slips to the other segment of the split ring, and the direction of the current and resulting forces reverses, as shown in Figure 28d. The momentum of the rotating coil takes it past the vertical zero torque position to that shown in Figure 28e. At this point, the downward force on segment A and the upward force on segment B provide the torque to continue the rotation.

Figure 29 shows the output torque of this motor as a function of time. The points on this curve, identified by letters, correspond to the lettered portions of Figure 28. This curve has the same shape as the electrical output of a d.c. generator, as shown in Figure 24. Just as generators provide a more constant voltage by using multiple poles, multiple-pole motors provide a more uniform torque. As in generators, the magnetic fields are usually provided by current-carrying coils rather than permanent magnets.

A wide variety of electric motors operating on both a.c. and d.c. currents are in common use today. Detailed descriptions of major types are contained in later modules.

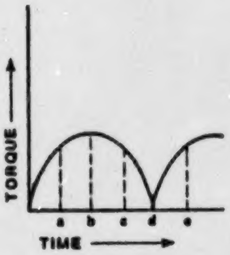


Figure 29. Output Torque of a Simple d.c. Motor.

TRANSFORMERS

Although electrical transformers are not electromechanical devices, they are often grouped for study with motors and generators because they operate on the same basic principles. Figure 30 shows the basic construction of a transformer. It consists of two coils of wire wound on a core consisting of

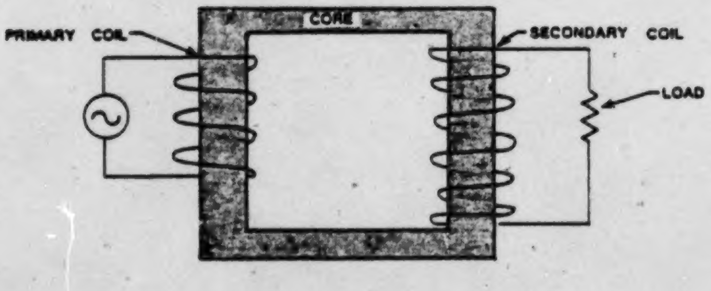


Figure 30. Basic Transformer.

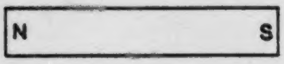
a magnetic material. The core provides a closed magnetic circuit for the magnetic fields within the transformer. An increasing current through the primary produces an increasing magnetic field through the transformer core. The changing field produces magnetic forces on electrons in the secondary coil. The voltage produced across each turn in the transformer coils is the same. In Figure 30, the secondary has twice as many turns as the primary. This means the output voltage will be twice the input voltage. Since the energy output of the transformer cannot exceed the energy input, the output current is limited to one-half the input current. Because transformers work on changes in the magnetic field, they cannot be used with d.c. voltages and currents.

Transformers and their construction and applications will be discussed in detail in a later module.

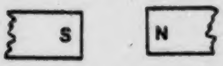
EXERCISES

1. Draw the magnetic fields in the following diagrams:

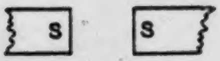
a.



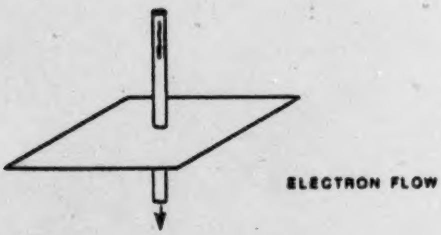
b.



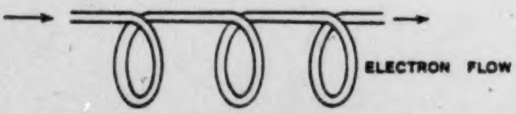
c.



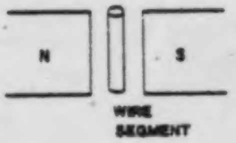
d.



e.

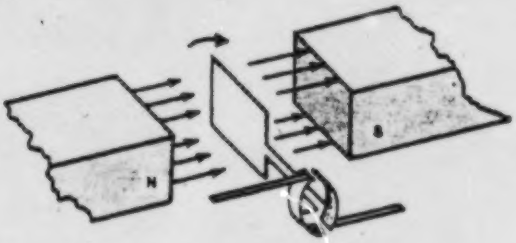


2. Determine the direction of force on electrons in the wire at the right if the wire moves ...
   a. out of the page toward the reader.
   b. toward the south pole of the magnet.

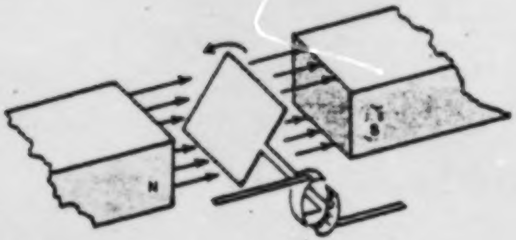


3. Indicate the direction of electron flow through the generator coil in the following diagrams. (Use the right-hand generator rule for electron flow presented in the text.)

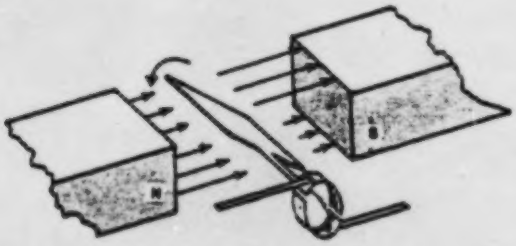
a.



b.

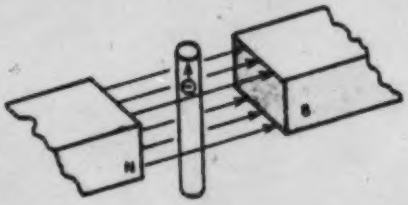


c.

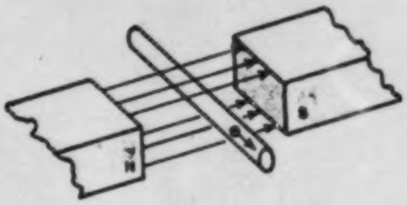


4. Determine the direction of the force on the current-carrying wires in the following diagrams. The direction of electron flow is indicated in each case.

a.

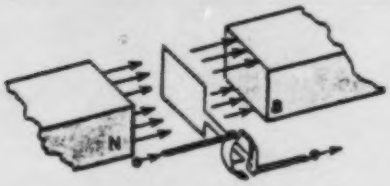


b.

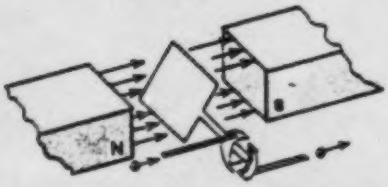


5. Indicate the direction of rotation of the current-carrying loops in the following diagrams. The direction of electron flow is indicated with an arrow in each case.

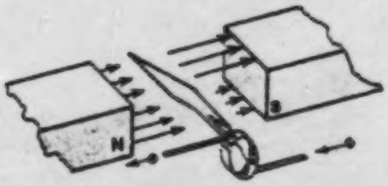
a.



b.



c.



LABORATORY MATERIALS

Two bar magnets
Iron filings
Sheet of white paper, 8-1/2" x 11"
Hard steel rod, 1/4" x 4"
Iron washers
12-V d.c. solenoid with core
0-12 V variable d.c. power supply with voltmeter and ammeter
0-20 lb spring scale
Support rods

LABORATORY PROCEDURES

1. Place one bar magnet on the table and cover with a sheet of paper. Sprinkle iron filings on the paper and observe the magnetic field of the bar magnet. Sketch the field in Part 1 of the Data Table.
2. Place two bar magnets in a straight line on the table with their north poles 1-1/2 inches apart. Place a sheet of paper over the magnets and sprinkle with iron filings. Sketch the field in the Data Table.
3. Repeat Step 2 with two south poles.
4. Repeat Step 2 with one north pole and one south pole.
5. Place several iron washers on the table and attempt to use the steel rod as a magnet to pick up the washers. Record the number of washers attracted to the rod in Part 2 of the Data Table.
6. Place the bar magnet at one end of the steel rod, as shown in Figure 31, and repeat. Record the number of washers attracted.

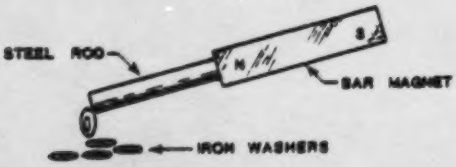


Figure 31. Magnetic Induction.

7. With the washers on the end of the steel rod, remove the magnet. Record the number of washers that remain attracted to the rod.
8. Magnetize the steel rod by drawing one pole of the bar magnet along the rod, as shown in Figure 32. Repeat the action several times, always using the same pole of the magnet and starting at the same end of the rod.

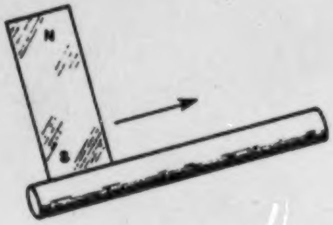


Figure 32. Magnetizing the Steel Bar.

9. Use the magnetized steel bar as a magnet to attract the iron washers. Record the number of washers attracted in Part 3 of the Data Table.
10. Remove the washers from the bar and throw the bar against the floor several times. Repeat Step 9.
11. Set up the d.c. power supply, solenoid, and spring scale, as shown in Figure 33. The solenoid must be firmly attached to the lab bench. C-clamps may be used.

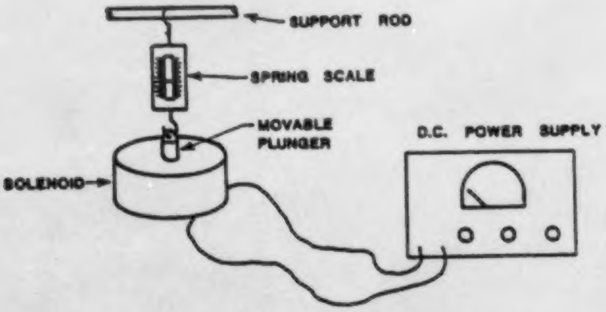


Figure 33. Measuring the Force of a Solenoid.

12. Set the d.c. power supply to 2 V. Measure the solenoid current and the downward magnetic force. Record in Part 4 of the Data Table.

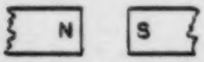
13. Repeat Step 12 at 2-V intervals until a total voltage of 12 V is reached. Raise the supported end of the spring scale as necessary.

DATA TABLE

DATA TABLE.

1. Magnetic Fields:

Sketch the following magnetic fields observed in the laboratory:



2. Magnetic Induction:

How many washers were attracted to the steel rod alone? _____

How many washers were attracted to one end of the steel rod with the magnet at the other? _____

How many washers remained when the magnet was removed? _____

Explain magnetic induction and how it was demonstrated by this experiment.

Data Table. Continued.

3. Magnetic Retension:

How many washers were attracted to the steel rod after it was magnetized? _____

How many washers were attracted to the steel rod after it was dropped? _____

Explain the loss of magnetism of the ro

4. A d.c. Solenoid:

Current (A)	Force on Core (lb)

What is the relationship of force to current?

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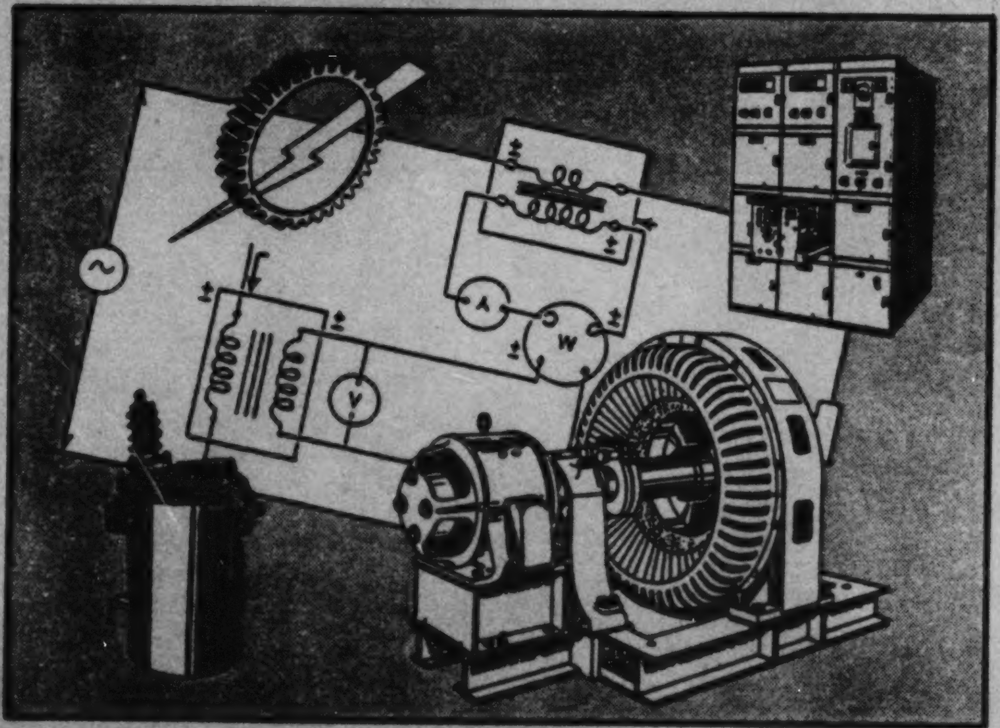
ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTROMECHANICAL DEVICES



MODULE EM-02

CONTROL ELEMENTS IN ELECTRICAL CIRCUITS

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

The importance of electromechanical devices is based on their roles in the production and application of electrical power — electricity — which is an important source of energy. Among these devices are the highly efficient electromechanical devices that do the following: link electrical and mechanical energy systems and contribute to the ease and efficiency with which electricity can be distributed and to the ease with which the flow of energy can be controlled in electrical systems.

This module discusses the basic control elements of electrical circuits: switches, relays, fuses, and circuit breakers. The first two, switches and relays, are used in the normal control functions of circuits; the second two, fuses and circuit breakers, provide automatic protection from damage due to over-current conditions. Most electrical systems incorporate several of these control mechanisms. They are grouped for study with electromechanical devices because of their importance in the control of such devices and because they are both electrical and mechanical in nature. In the laboratory, the student will construct several control circuits using switches and relays.

PREREQUISITES

The student should have completed Module EM-01 of "Electromechanical Devices."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Identify the schematic symbols for the following switches:
   a. Single pole, single throw
   b. Single pole, double throw
   c. Double pole, single throw
   d. Double pole, double throw
   e. Normally open, momentary push button
   f. Normally closed, momentary push button
   g. Rotary switch

2. Draw a diagram of a DPDT switch used to control four electrical circuits.
3. State the two most common contact materials in switches.
4. State the difference in a momentary action push button and a maintained action push button.
5. Draw and label a diagram showing the basic parts of a SPDT relay.
6. Describe the hazards of the following relay substitutions:
    a. A d.c. relay in an a.c. circuit
    b. An a.c. relay in a d.c. circuit
7. Draw and label diagrams for the following types of relay contact configurations:
    a. Break-make
    b. Make-break
    c. Double make-double break
8. Draw and label a diagram showing an RC filter used to extend the life of relay contacts in a d.c. circuit. Explain how the filter works.
9. Draw and label a circuit diagram of a locked-out relay.
10. Describe the operation of the following relays:
    a. Latching relay
    b. Reed relay
11. State the characteristics of the following types of fuses:
    a. Medium-lag
    b. Slow-blow
    c. Quick-acting
12. Draw and label diagrams showing two types of bimetallic circuit breakers in the open and closed positions.
13. Construct a locked-out relay control circuit in the laboratory.

SWITCHES

The most common control element employed in electrical circuits is the switch. The function of all switches is to complete or interrupt the circuit as desired, thereby controlling current flow through the circuit. Thousands of different switch configurations are commercially available. Virtually, every electric circuit in existence contains at least one switch, and most electrical systems employ several. A few of the more important classes of switches are described in the following paragraphs.

The most common type of switch is the toggle switch, which is illustrated in Figure 1. This switch consists of a pair of contacts mounted on flexible brass strips. When the switch is in the OFF position, the spring action of the upper brass strip separates the contacts and prevents current flow. When the switch is turned ON, a rocker made of an insulating material forces the upper brass strip to bend downward and causes the contacts to touch, thereby completing the circuit. The rocker contains a latching mechanism that maintains pressure on the switch contacts until the switch is turned off.

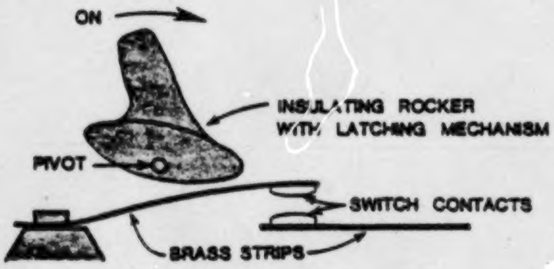


Figure 1. Basic Structure of Toggle Switch.

The voltage that the switch is capable of switching is determined by the separation of the contacts within the switch. The current rating of the switch depends upon the contact material and size and upon the voltage used in the circuit. The ideal contact material should have high electrical and thermal conductivity, a high melting temperature, high resistance to mechanical wear, and no tendency to form an oxide or tarnish film that would act as an electrical barrier. The material most often chosen for switch contacts is coin silver. Since silver forms a tarnish layer, the contacts are often designed to slide across one another slightly in a "wiping action" that cleans the contacts each time the switch is operated. Gold is also a popular material for switch contacts because of its excellent electrical properties and because it does not tarnish. Because of the cost, gold contacts consist of thin layers of gold over another metal such as silver or brass. Other materials used for switch (and relay) contacts include palladium, tungsten, and alloys of silver and cadmium.

Switch ratings are usually given in terms of both voltage and current. The following are typical ratings taken from manufacturers' specifications for three different switches:

- 5 A @ 28 V d.c.; 2 A @ 28 V a.c., 400 Hz; 3 A @ 60 Hz, 115 V a.c.
- a.c. switch; 6 A @ 125 V a.c.; 3 A @ 250 V a.c.
- 15 A @ 125 V a.c.; 10 A @ 250 V a.c.

This basic type of switch is available in several switch combinations packaged in one case with a common control. Figure 2 shows four such combinations. The SPST switch is used as the on-off switch in most household appliances and circuits. It interrupts the circuit at only one point. Such a switch is usually installed in the ungrounded side of a d.c. circuit and the "hot" side of a.c. circuits to maintain most of the circuit at zero potential when the switch is in the OFF position. The DPST switch is used when both sides of the power source are to be disconnected from the circuit.

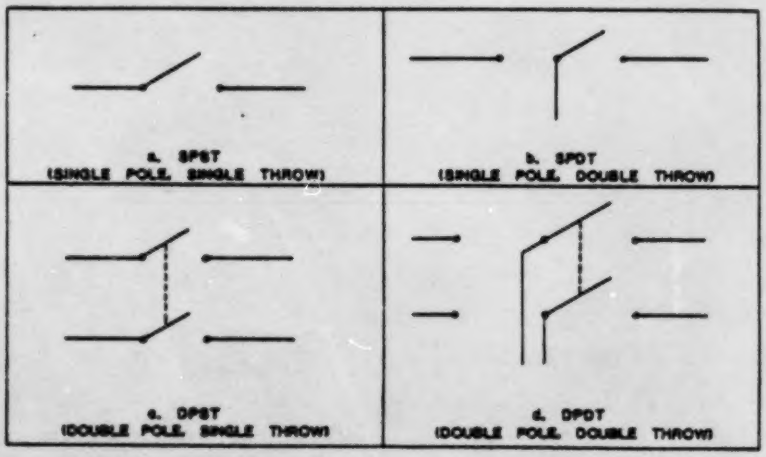

a. SPST (SINGLE POLE, SINGLE THROW)
b. SPDT (SINGLE POLE, DOUBLE THROW)
c. DPST (DOUBLE POLE, SINGLE THROW)
d. DPDT (DOUBLE POLE, DOUBLE THROW)

Figure 2. Switch Contact Configurations.

Double throw switches are used to connect power to one circuit while in one position and to another circuit while in another position. Figure 3 shows a DPDT switch used to control four circuits. In some cases, these switches

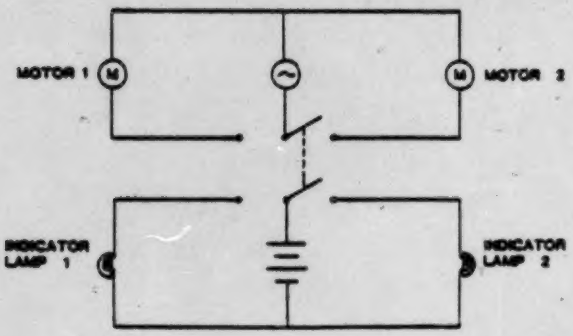
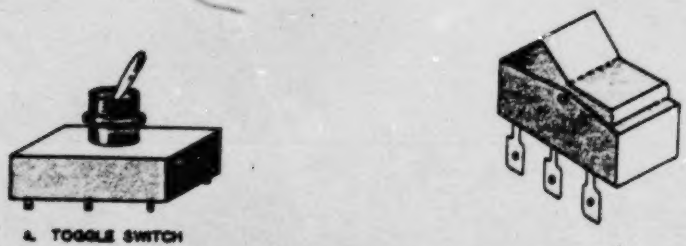


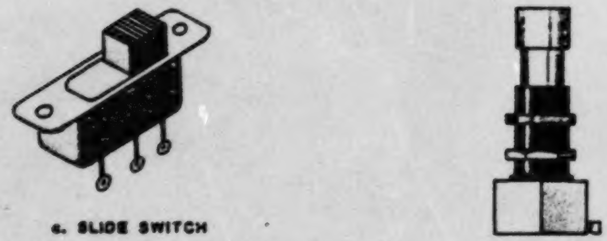
Figure 3. Control Circuit Using DPDT Switch.

have center OFF positions in which all circuits are broken, but others do not. Combinations with more switches are also available. A 4PDT switch, for example, has four poles, each of which can be connected to two separate circuits.

The schematic symbols shown in Figure 2 are used for several types of switches. Four of these are shown in Figure 4. Each of these are maintained action switches, which means that they remain in the position in which they are placed. The maintained action push-button switch contains a mechanism similar to that in a ball-point pen. One push turns it on; another turns it off.


a. TOGGLE SWITCH

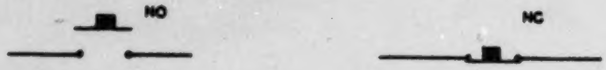
b. ROCKER SWITCH


c. SLIDE SWITCH

d. MAINTAINED ACTION PUSH BUTTON

Figure 4. Four Types of Switches.

Figure 5 shows the schematic representation of momentary push-button switches. This type of switch provides a momentary change in circuit conditions. The normally open push-button switch is an open circuit until it is pressed. Pressing the button closes the circuit, but it opens again when the button is released. The normally closed push button is a completed circuit that can be momentarily opened by pressing the button. Momentary push-button switches are used extensively in electrical control circuits.



a. NORMALLY OPEN PUSH BUTTON

b. NORMALLY CLOSED PUSH BUTTON

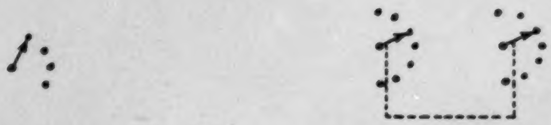
Figure 5. Momentary Push-Button Switches.

Figure 6 shows the construction of rotary switches. These switches are used whenever a large number of circuits must be switched at once in applications such as a television channel selector and the range switch of a volt-ohm-milliammeter. Figure 7 shows schematic representations of rotary switches. The contacts of rotary switches are usually made of brass, but they can be coated with silver or gold to improve performance.

a. SINGLE-GANG ROTARY SWITCH

b. THREE-GANG ROTARY SWITCH

Figure 6. Rotary Switches.



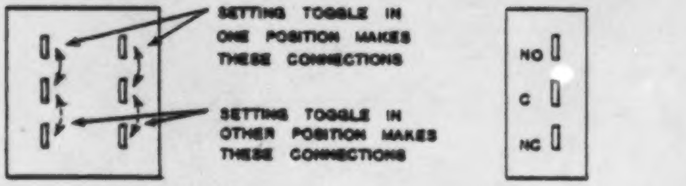
a. SINGLE-GANG 4 POSITION

b. TWO-GANG 6 POSITION

Figure 7. Schematic Representation of Rotary Switches.

TESTING AND MAINTENANCE OF SWITCHES

Switches can be checked for proper operation with an ohmmeter. An ohmmeter connected across the switch terminals should show infinite resistance when the switch contacts are open and zero resistance when the contacts are closed. (The actual resistance of closed switch contacts is a few milliohms.) This method can also be used to identify the switch functions associated with the various contacts. Figure 8a shows the terminal pattern of a DPDT switch. With the switch set in one position, each center terminal is connected to its respective upper terminal; with the switch set in the other position, each center terminal is connected to its respective lower terminal. This can be verified with the ohmmeter. Figure 8b shows the terminal arrangement of a typical momentary push-button switch. When the button is not depressed, the common terminal (C) is connected to the normally closed (NC) terminal; when the button is depressed, the common terminal is connected to the normally open (NO) terminal. This can also be verified with the ohmmeter. All switches can be checked in a similar manner.


SETTING TOGGLE IN ONE POSITION MAKES THESE CONNECTIONS
SETTING TOGGLE IN OTHER POSITION MAKES THESE CONNECTIONS
NO
C
NC

a. DPDT SWITCH

b. PUSH-BUTTON SWITCH

Figure 8. Switch Terminal Configurations.

If a switch is found to be defective, it can often be returned to service by the application of a spray-on contact cleaner, followed by several cycles of switch operation. This procedure will remove coatings from the contacts, thereby providing less electrical resistance. If mechanical defects exist within the switch, the switch should be replaced. Switches can sometimes be repaired, but additional failures usually occur in a short time.

RELAYS

A relay is an electromechanical device in which the flow of one electric current is used to control that of another. Figure 9 shows the basic components of a relay. A current-carrying coil is wound on one side of a U-shaped core. The other end of the core supports a movable armature made of a magnetically permeable material. The armature pivots vertically and is held away from the current coil by a tension spring.

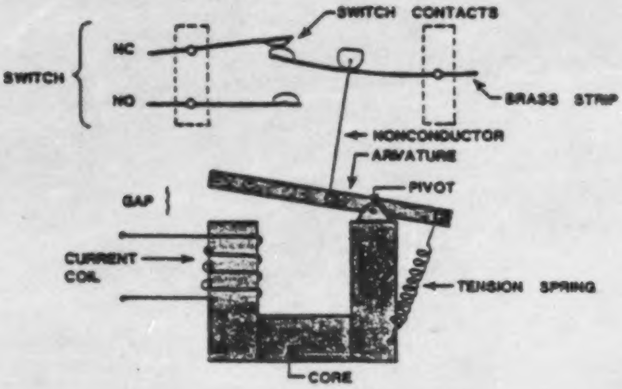


Figure 9. Parts of a Relay.

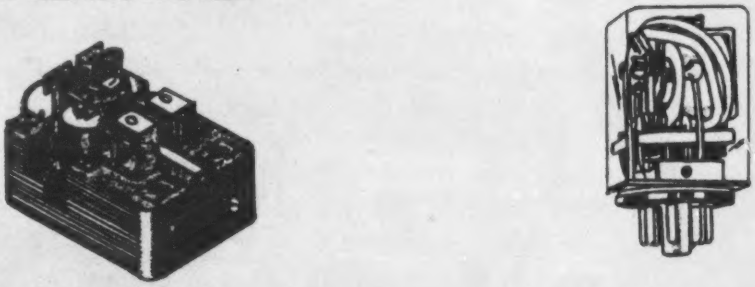
When a current flows in the coil, a magnetic field is produced. This field induces a strong magnetic field through the loop of magnetically permeable material formed by the core and armature. The result is a magnetic force of attraction across the gap between the core and armature. If this force is strong enough to overcome the tension in the spring, the armature will move down into contact with the core and stretch the spring. The armature is connected mechanically to the switch mechanism by a non-conductor of electricity. The switch consists of three brass strips terminated with silver or gold switch contacts. When the armature moves downward, it bends the center switch strip down until it breaks contact with the normally closed contact and makes contact with the normally open contact.

When the current through the coil is interrupted, the magnetic field through the core and armature disappears. The spring then opens the gap and returns the switch to the normally closed position.

The relay shown in Figure 9 is a single-pole, double-throw (SPDT) relay capable of switching two circuits. Relays are available in switch arrangements from SPST to double-throw relays with dozens of poles. Figure 10 shows several common relay configurations, all of which operate in the same manner except for the latching relay (Figure 10f). The latching relay operates on current pulses. Each pulse rotates a cam that operates the switch. The switch contacts reverse positions with each pulse.

a. TELEPHONE-TYPE RELAY

b. LOW-CURRENT RELAY



c. HIGH-CURRENT RELAY

d. PLUG-IN RELAY

e. CIRCUIT BOARD MOUNTED

f. LATCHING RELAY

Figure 10. Types of Relays.

Relays are specified according to the ratings of both the current coil and the switch contacts. Contacts — like switches — are rated according to current and voltage capabilities. Several switch configurations can be used. Three configurations and their schematic symbols are shown in Figure 11.

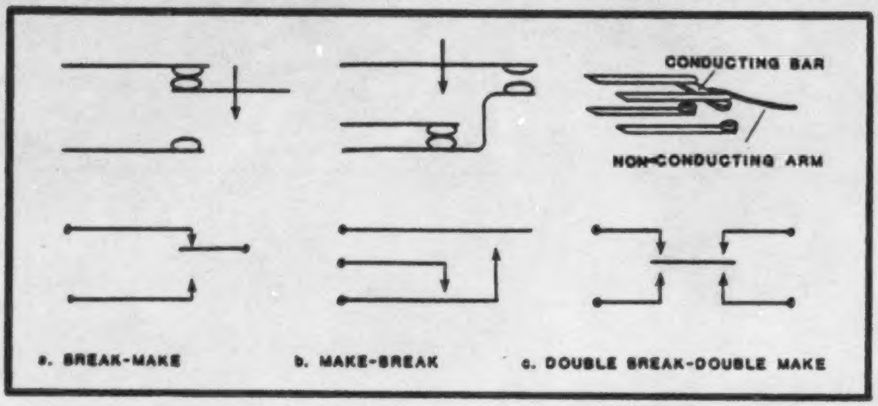


Figure 11. Relay Contact Configurations.

Figure 11a shows a "break before make," or "break-make," relay switch. In this case, one circuit is always interrupted before the other is completed. This is the most common arrangement. In the "make-break" relay switch shown in Figure 11b, one circuit is always completed before the other is broken — meaning that both circuits are completed for a short time. This type of relay is used in some d.c. motor control circuits. In the double break-double make switch in Figure 11c, a conducting bar is switched between two sets of contacts by a non-conducting arm. This type of switch is often employed in the control of large currents.

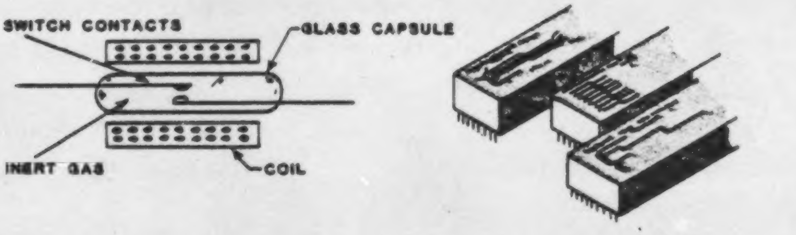
Relay coils are rated by their operating voltage and by whether they are a.c. or d.c. Standardized coil ratings are 6, 8, 10, 12, 24, 32, 48, 60, 115, 230 volts a.c. or d.c., and 440 volts a.c.

In a d.c. relay coil, the current is limited by the coil resistance only. The coil is designed to have a resistance that will result in the proper operating current when the rated voltage is applied to the coil. The d.c. relays usually energize at about 75% of their nominal rated coil voltage. Once energized, they will remain so until the current falls below 50% of their rated voltage.

In an a.c. relay coil, the current is limited by the total impedance, which is the sum of the resistance of the wire in the coil and the inductive reactance of the coil. Since the inductive reactance is high, the coil resistance is lower than that of a similar d.c. relay. When an a.c. relay coil is energized, the current initially surges to about 1.67 times the nominal operating current and then drops to the nominal value after the armature is closed and the alternating magnetic field is established. This means that a.c. relays close more rapidly than d.c. relays. Some a.c. relays close in as short a time as 5 milliseconds (ms), whereas d.c. relays require 15-70 ms.

The difference in coil design between a.c. and d.c. operated relays is the reason that the two types are not interchangeable. If a d.c. relay is used in an a.c. circuit at its rated voltage, the resistance of the coil combined with the a.c. inductive reactance is high enough to reduce the current to below the operating range when the relay closes. The result is "chatter," the rapid opening and closing of the contacts. If an a.c. relay is used in a d.c. circuit at its rated voltage, its coil resistance alone does not limit coil current to a safe level, and the coil overheats, destroying the relay.

Figure 12a shows another relay design, called a "reed relay." The switch elements of the reed relay consist of flexible pieces of magnetically permeable material. When a d.c. current flows through the coil, the magnetic fields induced in the switch elements cause their free ends to attract one another, making contact and completing the electrical circuit. Figure 12b shows several of these compact relays encapsulated for mounting on printed circuit boards.



a. PARTS OF A REED RELAY

b. REED RELAYS IN PRINTED CIRCUIT CASES

Figure 12. Reed Relays.

TESTING AND MAINTENANCE OF RELAYS

Testing a relay for proper functioning requires an ohmmeter and a voltage source compatible with the relay coil. The following steps will locate any relay malfunction.

1. With no power to the relay coil, use the ohmmeter to measure the resistance of each set of contacts. Connections across common and normally closed contacts should read "zero ohms"; connections across common and normally open contacts should show infinite resistance.
2. Apply the operating voltage to the relay and observe the operation of the relay. Turn the voltage off and on several times to be sure the relay is operating correctly.
3. With the relay coil energized, measure the resistance between the switch contacts again. In this case, the normally closed-to-common connection should have infinite resistance, and the normally open-to-common connection should read "zero."

The most common problem in relays is failure of switch contacts to make good electrical contact because of burns or corrosion. Such contacts can often be returned to proper operation through careful cleaning. Oxides and other materials can be removed from the contacts by using a fine abrasive paper. If the contacts are pitted or burned, they may be smoothed with a fine file; however, care should be used to ensure that the contacts retain their original shape to allow the normal wiping action to clean them during closing.

If the contacts are clean and the relay appears to operate normally but some switches still do not open or close properly, the problem is probably a mechanical one. The problem can be corrected by adjusting the tension in the relay spring or by carefully bending some of the brass strips that compose the relay switch. Such measures are usually only temporary remedies, and the damaged relay should be replaced as soon as possible.

The best preventive maintenance for any relay is to use models with dust covers and to be sure the covers are in place.

RELAY CIRCUITS

Relays are employed in a wide variety of control circuits. Two examples will be examined here.

Figure 13 shows a simple relay control circuit. The controlling circuit consists of a low voltage d.c. source, a switch, and the relay coil. When a current flows in the controlling circuit, the relay switch closes and a much larger current flows through the controlled circuit to operate the motor.

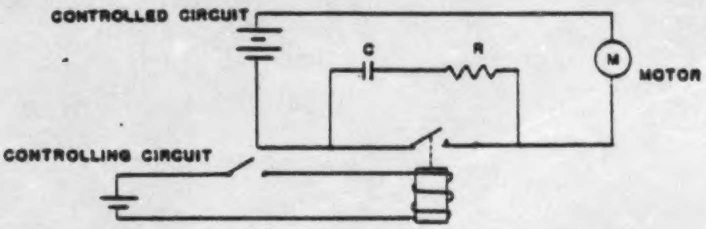


Figure 13. Simple Relay Control Circuit.

The resistor-capacitor filter shown in Figure 13 is often added across the contacts of high current d.c. relays to extend contact life. Most contact damage occurs when the contacts open and the current forms an arc between them for a few milliseconds. The RC filter prevents this type of damage, however. When the contacts begin to open, they are short circuited by a resistor and capacitor in series. The capacitor voltage is zero at this instant. The current flow that would have formed the arc now goes into charging the capacitor through the resistor. Thus, the voltage across the switch contacts rises gradually rather than abruptly. By the time the voltage is high enough to produce an arc, the contacts have moved so far apart that one cannot form.

Figure 14 shows a circuit called the "locked-out relay." This type of relay control circuit is common on many types of electromechanical machinery

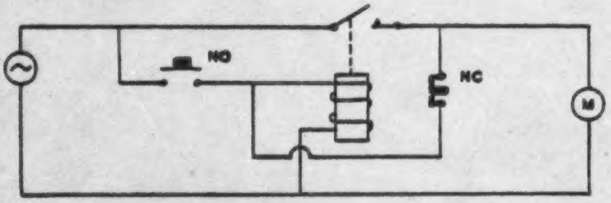


Figure 14. Locked-Out Relay.

and can be used in a.c. or d.c. circuits. It allows the control of large currents by means of two low-current push buttons that can be mounted in any convenient place.

Figure 14 shows the circuit in its unenergized state, with no current flowing. When the normally open push button is pressed, it conducts momentarily, allowing a current to flow through the coil and close the relay switch. The push button is then released. The coil continues to receive current through the now closed relay switch and the normally closed push button. This small current maintains the relay in the closed position and delivers the larger current to the motor. When the normally closed push button is depressed, the coil circuit is broken, and the relay opens.

FUSES

All electrical circuits are subject to failures. If a failure occurs that significantly reduces circuit impedance, the current in the circuit can reach levels that are damaging to circuit components. When this condition exists, the weakest link in the circuit will eventually "burn out" and open the circuit. A fuse is a deliberate weak link in a circuit and is designed to create an open circuit if a certain current level is exceeded for a certain period of time. This occurrence protects other circuit components from damage.

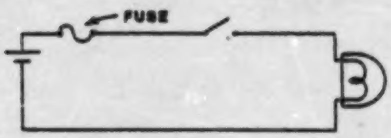


Figure 15. Fuse in a Simple Circuit.

Figure 15 shows the symbol for a fuse and the placement of the fuse in a simple electric circuit.

Figure 16 shows several types of fuses. Those shown are standard 1-1/4" by 1/4" fuses; however, similar types are available in a wide variety of sizes and ratings. Fuses can be grouped in the following three categories:

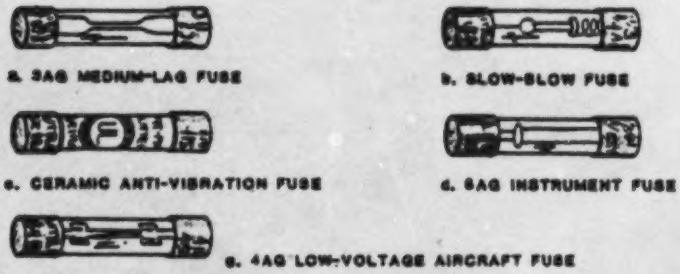
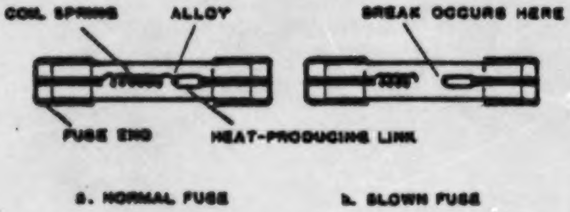

a. 3AG MEDIUM-LAG FUSE
b. SLOW-BLOW FUSE
c. CERAMIC ANTI-VIBRATION FUSE
d. 8AG INSTRUMENT FUSE
e. 4AG LOW-VOLTAGE AIRCRAFT FUSE

Figure 16. Types of Fuses.

1. Medium-lag fuses are the least expensive and most common. They can carry their rated current continuously without blowing and are capable of 110% of their rated current for an hour or more. At 135% load, they blow in less than an hour. At 200% load, they blow in under 30 seconds. At higher currents, they blow more quickly.
2. Slow-blow fuses are used in circuits that routinely have current surges that would overload a medium-lag fuse. This is the case with most circuits involving electric motors. The slow-blow fuse uses the heating effect of a current through a resistor to melt a solder-like alloy. Short-term overloads do not produce enough heating to melt the alloy; but long-term overloads melt the connection, and an internal spring separates the parts of the fuse, as shown in Figure 17.



a. NORMAL FUSE

b. BLOWN FUSE

Figure 17. Action of a Slow-Blow Fuse.

3. Quick-acting fuses, also called "instrument fuses" because that is one of their most important applications, are designed to blow quickly in order to protect delicate meters and other circuitry from accidental overloads. A quick-acting fuse will blow in 5 seconds at 200% load and can blow in 5 milliseconds at high loads.

CHECKING AND REPLACING FUSES

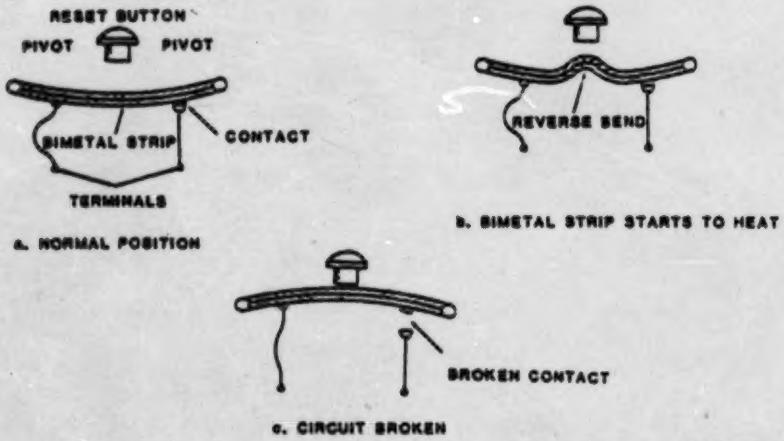
Many fuses have glass bodies and can be visually inspected for continuity. However, a fuse can look good and still be bad because the break in the conductor may be at one end of the fuse element. The best way to determine if a fuse that looks good is good is to check its resistance with an ohmmeter.

A fuse blows only when some circuit irregularity has occurred. Before replacing the fuse, an attempt should be made to determine why it blew, and steps should be taken to prevent a similar problem in the future. Fuses should be replaced only with replacements with the same rating. Practices such as shorting fuse terminals together or using high current fuses in low current circuits defeat the purpose of the fuse and should be avoided.

CIRCUIT BREAKERS

The use of circuit breakers as circuit protection devices combines the protection of fuses with the advantage of returning the circuit to operation with the press of a button or switch.

Thermal-type circuit breakers have characteristics similar to those of slow-blow fuses. Figures 18 and 19 show the construction and operation of two such circuit breakers. The basic bimetallic breaker shown in Figure 18 consists of a current-carrying bimetallic strip with switch contacts at one end. When the current exceeds the rated value, the bimetallic strip heats and begins to bend in the reverse direction from its cool position. It eventually snaps into the open position shown in Figure 18c and remains there until reset.



a. NORMAL POSITION

b. BIMETAL STRIP STARTS TO HEAT

c. CIRCUIT BROKEN

Figure 18. Operation of Basic Bimetallic Circuit Breaker.

The circuit breaker shown in Figure 19 uses the heating of a bimetallic strip to unlatch contacts held together by the spring force on the contacts. Once the contact is broken, the spring force separates the contacts until the reset button is pressed.

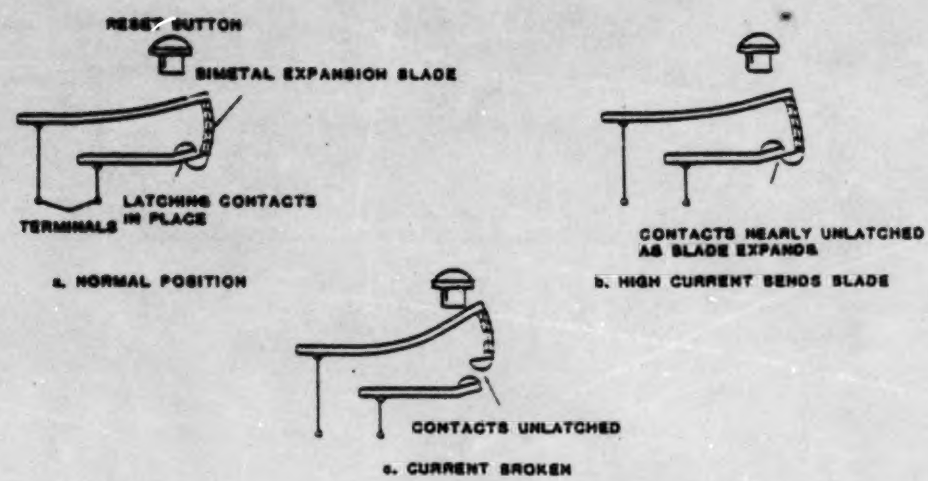

RESET BUTTON
BIMETAL EXPANSION BLADE
LATCHING CONTACTS IN PLACE
TERMINALS
a. NORMAL POSITION
CONTACTS NEARLY UNLATCHED AS BLADE EXPANDS
b. HIGH CURRENT BENDS BLADE
CONTACTS UNLATCHED
c. CURRENT BROKEN

Figure 19. Circuit Breaker That Uses Unlatching Action.

Bimetallic circuit breakers are available in a wide variety of ratings and are widely used in residential and industrial circuits.

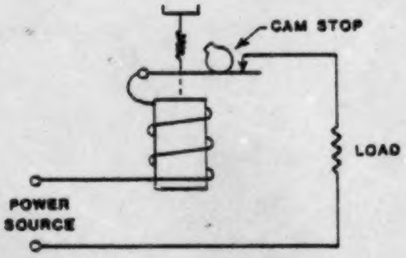

CAM STOP
LOAD
POWER SOURCE

Figure 20. Magnetic Circuit Breaker.

Circuits requiring a faster action than that provided by bimetallic circuit breakers can be protected with the magnetic circuit breaker, as shown in Figure 20. This device consists of a normally closed relay switch operated by a coil in series with the circuit load. All of the circuit current passes through the coil of the circuit breaker. If the current exceeds the rated value, the relay armature is pulled down, opening the circuit, and a cam stop falls into place to keep the circuit open until it is reset.

CHECKING CIRCUIT BREAKERS

The continuity of a circuit breaker in the closed position can be checked easily with an ohmmeter; but the only way to determine if a circuit breaker opens when it should is to test it under a current load. Thermal circuit breakers should open within 20 seconds at 200% of their current rating.

Magnetic circuit breakers generally open faster, but the specifications of each type should be checked because of the large range in opening times of these devices.

EXERCISES

1. Describe the procedures for checking the function of the following with an ohmmeter:
   a. Toggle switches
   b. Momentary push-button switches (both NO and NC)
   c. Fuses
   d. Normally closed relay contacts
   e. Normally open relay contacts
2. Obtain an electronics supplier's catalog such as the Newark catalog listed in the references. Look up an example of each of the following items and list all specifications given for the item chosen.
   a. Toggle switch
   b. Momentary action push-button switch
   c. Rocker switch
   d. Rotary switch
   e. General purpose a.c. relay
   f. General purpose d.c. relay
   g. Dry reed relay
   h. Magnetic circuit breaker
   i. Thermal circuit breaker
   j. Ceramic body fuse
   k. Slow-blow fuse
   l. Instrument fuse

LABORATORY MATERIALS

Three colored pencils
VOM
6-volt battery

Connecting wires

115-V a.c. power cord with connectors compatible with relay

115-V a.c. outlet with connectors compatible with relay

Small 115-V a.c. motor (such as a fan)

The following components attached to a board and provided with terminals for connecting wires: DPST switch; NO momentary push-button switch; NC momentary push-button switch; 6-V d.c. relay with DPDT switch and removable dust cover; two 6-V lamps with red and green lenses

LABORATORY PROCEDURES

1. Using the ohmmeter function of the VOM and the procedures described in the Subject Matter, check each of the switches for proper functioning. Label the common, normally open, and normally closed terminals of the push-button switches.
2. Use the VOM to check continuity of the normally closed relay contacts. Energize the relay coil by connecting it directly to the 6-volt battery, and check the continuity of the normally open relay contacts. Label all relay terminals.
3. Connect the relay control circuit shown in Figure 21.

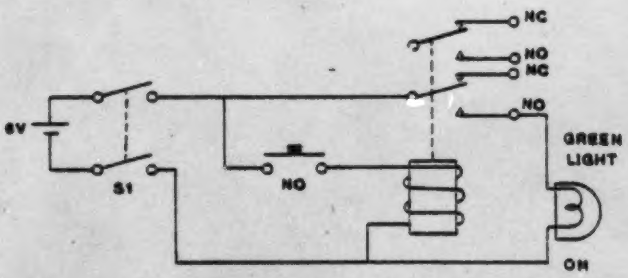


Figure 21. Simple Relay Circuit.

4. Turn on the power switch. Press the push button and observe the operation of the simple relay circuit.
5. Identify the current paths of the controlling circuit and the controlled circuit on Figure 21 and on the working circuit.

6. Turn off the power switch and add the second lamp, as shown in Figure 22.

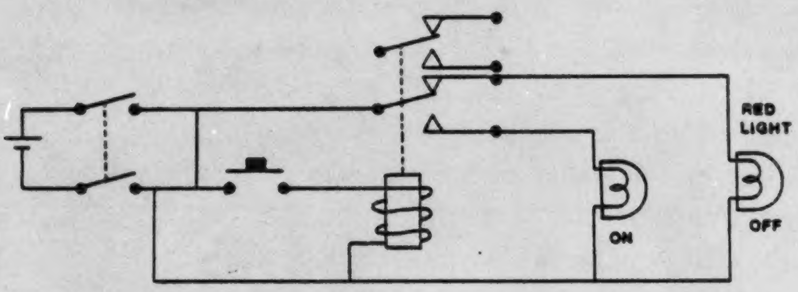


Figure 22. Addition of OFF Indicator Light.

7. Turn on the power. Press the push button and observe the operation of this circuit.
8. Turn off the power switch and add the normally closed push button, as shown in Figure 23. This completes the locked-out relay control circuit.

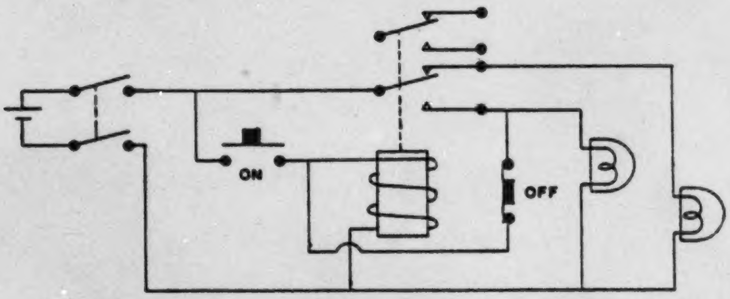


Figure 23. Completed Locked-Out Relay Control Circuit.

9. Turn on the power switch. Alternately press the two push buttons and observe the operation of the circuits.
10. Turn off the power switch. Connect the a.c. power cord, a.c. outlet, fan, and upper switch of relay, as shown in Figure 24.

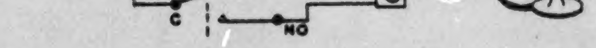


Figure 24. An a.c. Circuit.

11. Plug the a.c. power cord into an a.c. outlet, using caution not to come into contact with the 115-V a.c. potential present in the circuit. Turn on the power switch of the 6-V control circuit. Alternately press the two push buttons and observe circuit operation.
12. Turn off the power switch and unplug the a.c. power cord from the outlet.
13. Remove the dust cover from the relay and sketch the relay mechanism in the Data Table.
14. Complete the Data Table, referring to the experimental circuit as necessary.
15. Disassemble the experimental setup.

DATA TABLE

DATA TABLE.

1. Draw and label the part of the relay used in this experiment in the OFF and ON positions.

2. Draw a complete schematic of the final circuit used in Step 11 of the procedures. Indicate the following current paths in three different colors:
   a. Current path for initially energizing the relay coil
   b. Current path for maintaining a relay coil current
   c. Current path for operation of an a.c. motor

Data Table. Continued.

3. Describe in detail the operation of the above circuit. Include the function of each component.

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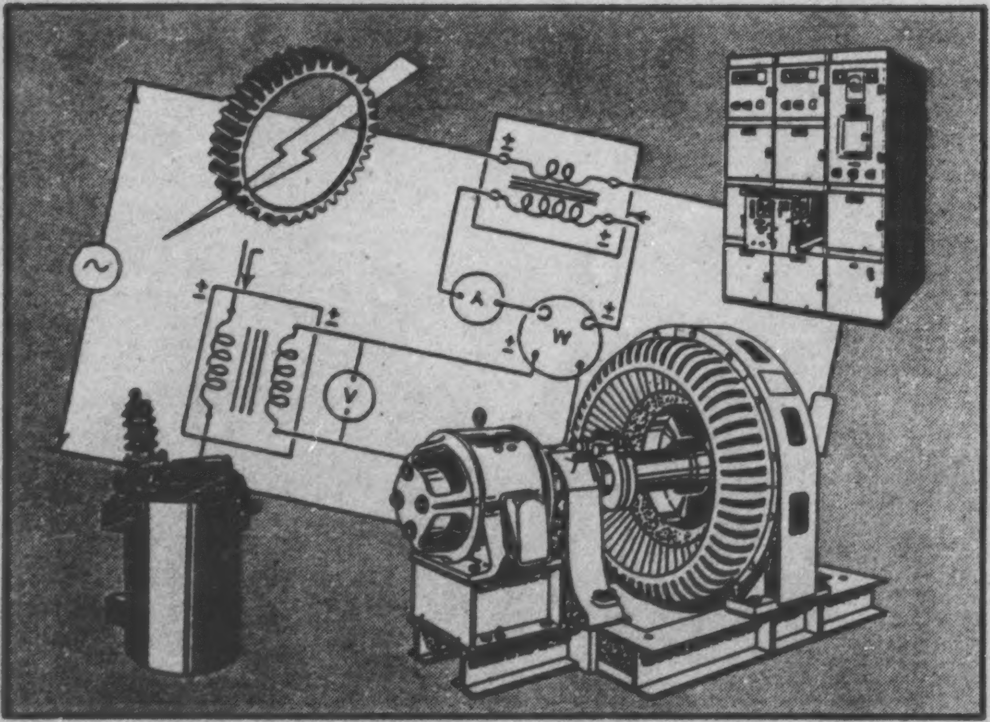
ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTROMECHANICAL DEVICES



MODULE EM-03

TRANSFORMERS

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

A transformer is a device used in an a.c. electrical system to increase voltage and decrease current or to decrease voltage and increase current, thus matching the impedance of the load to that of the a.c. power source. While transformers are not electromechanical devices, they are studied in this course because their function is based on the same magnetic principles that operate in electromechanical devices. The ability to transform a.c. current and voltage is the chief reason that virtually all commercial electrical power systems operate on alternating current.

This module discusses the principles of transformer operation and the construction details of several types of transformers. Factors leading to power losses are identified, as well as methods of minimizing such losses. The connection of transformers in single-phase and three-phase circuits is presented, as are methods of troubleshooting transformers. In the laboratory, the student constructs two experimental circuits and measures the efficiency of a power transformer.

PREREQUISITES

The student should have completed Module EM-02 of "Electromechanical Devices" and have an understanding of a.c. circuit analyses.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Draw and label a diagram of a simple transformer.
2. Explain how a transformer operates, using a graph showing primary current, magnetic field strength, and secondary current as functions of time.
3. Given three of the following quantities for a transformer, determine the fourth:
    a. Primary voltage
    b. Secondary voltage

   c. Primary current
   d. Secondary current
4. Given two of the following quantities for a transformer, determine the third:
   a. Input power
   b. Output power
   c. Efficiency
5. Explain the following sources of power loss in a transformer and the steps necessary to reduce each:
   a. Hysteresis loss
   b. Eddy currents
   c. Copper loss
6. Draw and label diagrams showing the coils and core of the following transformer types:
   a. Core-type
   b. Shell-type
7. Explain two functions of the oil in an oil-filled transformer.
8. Given the specifications of a single-phase transformer with dual primaries and dual secondaries, draw diagrams showing possible coil connections, and state the output voltage and current ratings for each connection for a specified input voltage.
9. Draw schematic diagrams of the four possible connections of three-phase transformers. State which of these is seldom used and state an advantage of each of the other three connections.
10. For each of the above connections, given the input voltage and currents and the ratio of windings of the transformers, determine the output voltages and currents.
11. State two advantages and one disadvantage of an autotransformer and explain its construction.
12. Draw and label diagrams showing the use of the following instrument transformers:
    a. Current transformer
    b. Voltage transformer
13. Explain why high-frequency transformers have air cores.

14. Explain the operation of a constant current transformer used in lighting circuits.
15. Explain how to use a VOM to check continuity of transformer windings and why a VOM cannot be used to check for shorted windings.
16. Given the appropriate equipment, measure the input and output power of a transformer with varying input voltage and determine transformer efficiency.

THE BASIC TRANSFORMER

Figure 1 shows the basic components of a transformer used for the transformation of alternating currents and voltages. The transformer core is a closed loop of magnetically permeable material. Two coils of wire are wound around the core. The primary winding is attached to an a.c. power source, and the secondary winding is connected to the load. The following discussion of transformer operation is based upon an ideal transformer having no losses and a power factor of one. Loss factors in practical transformers will be discussed in a later section of this module.

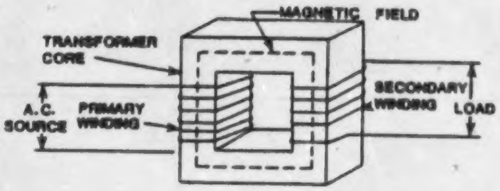


Figure 1. Basic Transformer Construction.

Figure 2 shows the primary current, magnetic field, and secondary current of a transformer in operation. The current flow in the primary coil produces a magnetic field in the transformer core. This magnetic field varies with the primary current changing direction when the current changes direction, as shown in the figure. The field also passes through the secondary coil. When the strength of the magnetic field passing through the secondary coil changes, a current is produced in the coil. When the magnetic field is at a maximum, its value is not changing, and the secondary voltage is zero, as indicated at points A and B of Figure 2. When the magnetic field is changing direction (zero magnitude of the field), the rate of change of the field is at the maximum, and the induced secondary current is also at a maximum, as indicated at points C and D of Figure 2. Because the induced current depends on change in the magnetic field, transformers operate on a.c. currents only. A constant d.c. current produces a constant magnetic field and, thus, will not induce a current in the secondary.

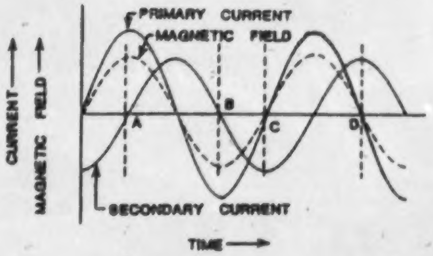


Figure 2. Transformer Operation.

If all the magnetic field passes through both coils and if the resistance of the windings is ignored, the maximum voltage across each turn of wire is the same in both the primary and the secondary. For example, suppose a transformer has 100 turns in the primary, 200 turns in the secondary, and a voltage of 10 V a.c. is applied to the primary. Each turn in the primary has a voltage drop of 0.1 V. Since each turn in the secondary also has a voltage of 0.1 V, the output voltage of the secondary is 20 V. This relationship is expressed in Equation 1.

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} = a \qquad \text{Equation 1}$$

where: N_1 = Number of turns in the primary.
N_2 = Number of turns in the secondary.
V_1 = Voltage on primary.
V_2 = Voltage on secondary.
a = Turn ratio of transformer.

A transformer connected to produce a voltage increase is called a "step-up transformer"; the same transformer connected to produce a voltage decrease is called a "step-down transformer."

The power in an electrical circuit is the instantaneous product of the current and voltage in the circuit. In the ideal transformer, all the power in the primary circuit is transferred to the secondary circuit. Thus, the product of voltage and current is the same for each circuit. This means that a transformer that increases output voltage decreases output current by a proportional amount; a transformer that decreases voltage increases current. This relationship is expressed in Equation 2.

$$\frac{N_1}{N_2} = a = \frac{I_2}{I_1} \qquad \text{Equation 2}$$

where: I_1 = Primary current.
I_2 = Secondary current.

Examples A and B show the use of Equations 1 and 2 in solving problems.

EXAMPLE A: DETERMINING TRANSFORMER OUTPUT.

Given: A transformer has 500 turns in the primary and 250 turns in the secondary. The primary current is 5 A and the primary voltage is 200 V.

Find:
(a) Turn ratio of transformer
(b) Output voltage
(c) Output current
(d) Input power
(e) Output power

Solution: (a) Turn Ratio:

$$a = \frac{N_1}{N_2}$$

$$= \frac{500}{250}$$

$$a = 2$$

(b) Output Voltage:

$$V_2 = \frac{V_1}{a}$$

$$= \frac{200\ \text{V}}{2}$$

$$V_2 = 100\ \text{V}$$

(c) Output Current:

$$I_2 = aI_1$$

$$= (2)(5\ \text{A})$$

$$I_2 = 10\ \text{A}$$

(d) Input Power:

$$P_1 = IV$$

$$= (5\ \text{A})(200\ \text{V})$$

$$P_1 = 1000\ \text{VA}$$

(e) Output Power:

$$P_2 = (10\ \text{A})(100\ \text{V})$$

$$P_2 = 1000\ \text{VA}$$

The transformer reduces the voltage by one-half and doubles the current, resulting in an output power equal to the input power.

EXAMPLE B: DETERMINING PRIMARY CURRENT.

Given: A transformer produces an output voltage of 24 V with an input voltage of 115 V. The secondary current is 2 A.

Find: Primary current by (a) calculating turn ratio and (b) calculating transformer power.

Solution: (a) Turn Ratio:

$$a = \frac{V_1}{V_2}$$

$$= \frac{115\ V}{24\ V}$$

$$a = 4.79$$

Primary Current:

$$I_1 = \frac{I_2}{a}$$

$$= \frac{2\ A}{4.79}$$

$$I_1 = 0.417\ A$$

(b) Output Power:

$$P_2 = IV$$

$$= (2\ A)(24\ V)$$

$$P_2 = 48\ VA$$

Input Power:

$$P_1 = P_2 = 48\ VA$$

Input Current:

$$I_1 = \frac{P_1}{V_1}$$

$$= \frac{48\ VA}{115\ V}$$

$$I_1 = 0.417\ A$$

When an ideal transformer has its primary connected to an a.c. source and its secondary open, the secondary voltage is that determined with Equation 1, and both the primary and secondary currents are zero. If a load is attached to the secondary, a current flows through the secondary to provide power to the load. The primary current increases to provide the necessary input power to the transformer. Thus, the power through the transformer and both the primary and secondary currents depend on the load connected to the transformer secondary. The impedance of the load must be high enough to limit the secondary current to the rated value at the rated output voltage. If the load impedance is too low, the current will increase above the rated value, and the transformer will overheat and be damaged.

POWER LOSSES IN TRANSFORMERS

The concept of an ideal transformer with 100% efficiency is useful in studying the operation of transformers, but such devices cannot be constructed. Some power loss always occurs.

Copper loss is the power loss resulting from current flow through the resistance of the coils. This loss is I^2R, where "I" is the coil current and "R" is the coil resistance. Thus, copper loss increases with the square of the transformer current. Copper loss can be reduced by using larger (lower resistance) conductors for the coils. The increased efficiency is achieved at the expense of increased size, weight, and cost.

Core loss in a transformer is the power loss within the transformer core. The two components of core loss are eddy currents and hysteresis loss.

Figure 3 shows the formation of eddy currents in a solid transformer core. These currents are induced in the ends of the core just as the secondary current is induced in the secondary coil. Losses due to eddy currents in the core are I^2R losses, and they increase as transformer current increases. These losses can be greatly reduced, but never entirely eliminated, by the

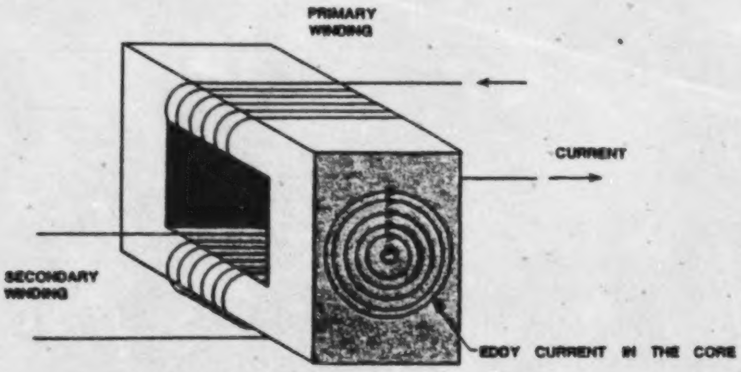


Figure 3. Path of Eddy Currents in a Solid Iron Core.

use of a laminated core transformer (Figure 4). This core consists of a stack of thin, metal plates coated with an electrical insulating material that prevents current flow between the plates. Eddy currents still exist in the individual core sections, but their magnitude and, thus, the resulting power loss, is greatly reduced.

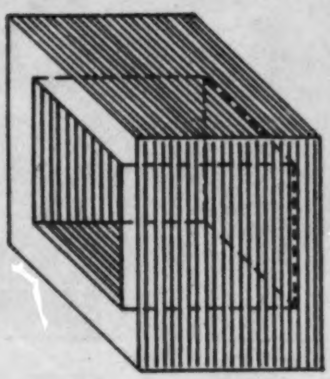


Figure 4. Laminated Core Transformer.

Hysteresis, discussed in Module EM-01, is the process of realigning the magnetic domains within the core when the direction of the applied magnetic field changes. Some energy is required for this realignment. Hysteresis loss is reduced by choosing a core material that is easily magnetized and remagnetized. Silicon steel is the material most commonly used. Unlike other loss factors, hysteresis loss is constant and does not vary with transformer current. Constant hysteresis loss accounts for the small current flowing in the transformer primary even when the secondary is open.

All power losses in the transformer appear as heat energy, which raises the temperature of the core and the windings. Transformers must be designed to dissipate this thermal energy at their rated values.

The efficiency of a transformer, as in all other energy transformation devices, is given by Equation 3.

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \qquad \text{Equation 3}$$

where: η = Percent efficiency.
P_{in} = Input power.
P_{out} = Output power.

The efficiency of power transformers varies from about 90% for small models to as great as 99% for large distribution transformers. A large power transformer is designed to operate at its maximum efficiency, at its rated primary and secondary voltages and currents, and at a specific frequency. Example C illustrates the calculation of transformer efficiency.

EXAMPLE C: CALCULATING TRANSFORMER EFFICIENCY.

Given: A power distribution transformer has an input power of 5 kVA and an output power of 4.925 kVA.

Find: Transformer efficiency.

Solution:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

$$= \frac{5\ \text{kVA}}{4.925\ \text{kVA}} \times 100$$

$$\eta = 98.5\%$$

POWER TRANSFORMERS

Transformers are manufactured in a variety of configurations for several applications. The most common type is called the "power transformer" because it is used to supply a.c. power to a load. Power transformers vary in size from 100,000 kVA models that are the size of a house to the tiny transformers that supply a few watts in radios and calculators. All power transformers have characteristics in common.

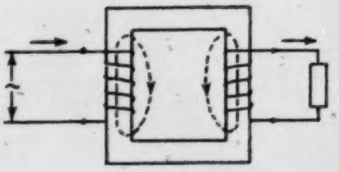


Figure 5. Primary and Secondary Leakage Fluxes.

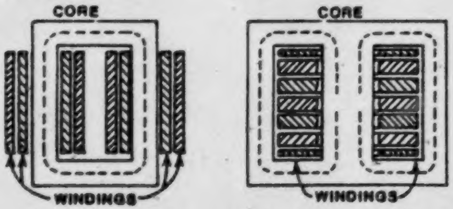


Figure 6. Transformers.

The ratio of input-to-output voltage is the same as the ratio of primary-to-secondary turns only if all the magnetic flux passes through both coils. Figure 5 shows that this is not the case in the simple transformer. This flux leakage is reduced in power transformers by winding the coils as shown in Figure 6. The core type (Figure 6a) consists of a rectangular core with coils around two sides. Each set of coils has a primary coil and a secondary coil. In the shell-type transformer (Figure 6b), all of the coils are wound around the central part of the core. The outer portions of the core surround the coils with a magnetic "shell." The windings of large-shell transformers usually consist of several thin secondary and primary coils stacked alternately. In smaller models, one coil surrounds the other.

Power transformers may be dry or oil-filled. Both types are shown in Figure 7. Most small transformers are the dry type. The coils consist of enameled copper wire, separated by paper and asphalt or resin insulation.

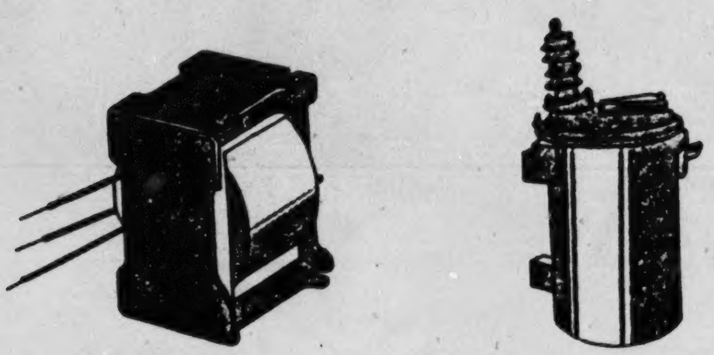


Figure 7. Power Transformers.

Transformers larger than 5 kVA are usually oil-filled. The coils are composed of copper wires with a porous insulation, such as cotton, and are immersed in a case filled with oil. The oil provides electrical insulation and heat transfer. Oil channels through the core and windings allow heated oil to rise through the center of the transformer. The hot oil then flows by convection down the inside of the case, transferring its heat energy through the wall to the outside air. Larger models may be equipped with radiators and cooling fans.

Transformers are available with several primaries and secondaries. The most common type of power transformer is the dual primary, dual secondary transformer represented schematically in Figure 8. Four possible connections are shown. This transformer is rated as 2300/4600 V input, 115/230 V output — which means that the transformer can produce an output voltage of 115 V or 230 with an input of either 2300 V or 4600 V. The primaries and secondaries are connected in series, or parallel, to produce the desired outputs. The voltage across one primary coil is always the lower of the primary ratings — 2300 V in this case. If a 4600 V input is used, the primaries are connected in series so that each operates at the desired voltage. Likewise, the voltage across one secondary coil is always the lower of the secondary ratings.

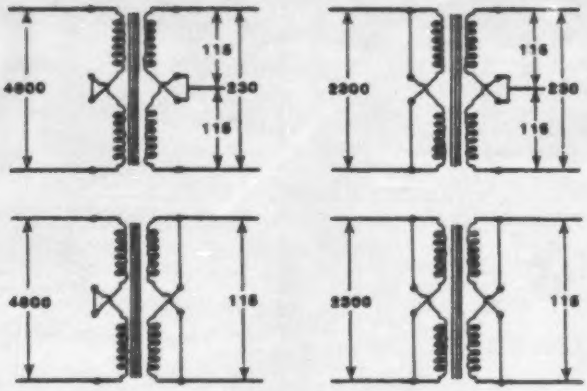


Figure 8. Transformer Connections.

Power transformers are also rated according to their power or output current. Distribution transformers and most other large transformers are rated by power in kilovolt-amps (kVA), rather than watts, because the actual power transfer in reactive circuits with low power factors may be much less than the product of voltage and current, upon which the interal power dissipation of the transformer depends. Smaller power transformers, such as those found in power supplies for electronic circuits, are often rated according to output current. The transformer used in the laboratory section of this module, for example, is rated as primary 115/230 V, secondary 12/24 V, secondary current 4/2 A — which means that the transformer can deliver either 4 amps at 12 volts or 2 amps at 24 volts from a source of 115 V or 230 V. The possible connections are the same as those shown in Figure 8.

Since most large-scale power systems are three-phase systems, the connection of transformers in three-phase circuits is important. A three-phase transformer consists of three identical single-phase transformers connected in one of the four ways illustrated in Figure 9. In this figure, the heavy lines represent the transformer coils. The windings on the left are the primaries, and those on the right are the secondaries. Each primary winding is mated in one transformer with the secondary winding drawn parallel to it. The line-to-line voltages and the currents are expressed in terms of the input voltage and current and the turn ratio "a."

The Y-Δ connection (Figure 9a) is commonly used in power distribution systems in stepping down from a high voltage to a low, or intermediate,

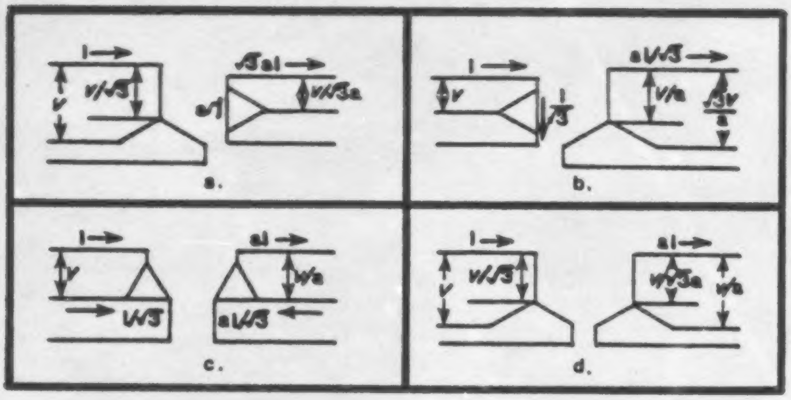


Figure 9. Common Three-Phase Transformer Connections.

voltage because it provides a desirable common ground for the high-voltage side. Conversely, the Δ-Y connection is most often used for stepping up to a higher voltage. The Δ-Δ connection has the advantage that one transformer can be removed for repair, whereas the remaining two continue to function as a three-phase bank rated at 58% of the original bank. The Y-Y connection is seldom used because problems with harmonics often produce non-sinusoidal outputs.

Example D illustrates the calculation of the output voltage and current of a three-phase transformer.

EXAMPLE D: THREE-PHASE TRANSFORMER.

Given: A three-phase transformer bank connected Y-Δ has line-to-line input voltages of 2400 V and a current of 10 A in each phase. The turn ratio of the transformer is 5.77.

Find: Output voltage and current.

Solution: From Figure 9a:

$$V_{out} = \frac{V_{in}}{a\sqrt{3}}$$

$$= \frac{2400 \text{ V}}{(5.77)(1.732)}$$

$$V_{out} = 240 \text{ V}$$

$$I_{out} = a\sqrt{3}\ I_{in}$$

$$= (5.77)(1.732)(10 \text{ A})$$

$$I_{out} = 100 \text{ A}$$

Power transformers are often provided with multiple taps for adjusting the input or output voltages. Figure 10 is a schematic of such a transformer designed to produce one of three outputs from one of two inputs. In such a transformer, the taps can be changed to produce the desired voltage under a range of input and output conditions.

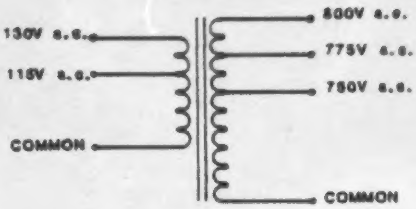


Figure 10. Multi-Tap Secondary.

AUTOTRANSFORMERS

Figure 11 shows the schematic diagrams of autotransformers. The autotransformer consists of a single winding that serves as both primary and secondary. The section of the winding that carries both the input and output currents is usually of a larger conductor than the remainder of the coil. Autotransformers can be used whenever both the input and output have a grounded line. Many small single-phase distribution transformers are autotransformers.

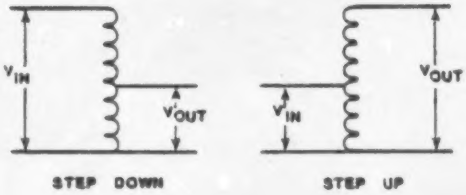


Figure 11. Autotransformer.

The autotransformer offers two advantages over transformers with separate windings. First, they are smaller, lighter in weight, and use less copper. Second, because there is only one coil, flux leakage is minimized. The most serious disadvantage of the autotransformer is that it provides no isolation of the load from the power line.

An ordinary transformer can be used as an autotransformer, if connected as shown in Figure 12.

Figure 13 shows a variable autotransformer and its schematic diagram. This transformer consists of a single coil of wire wound around a doughnut-

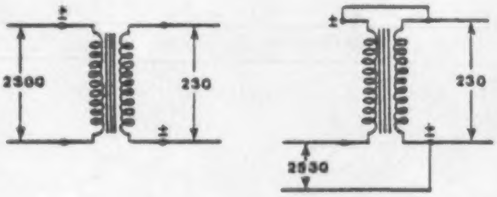
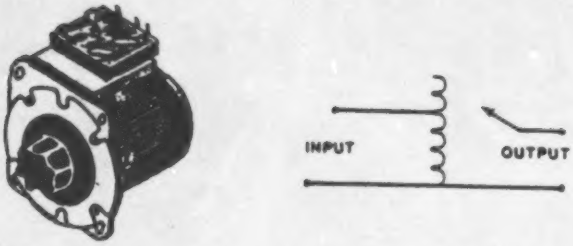


Figure 12. Connection of a Two-Winding Transformer as an Autotransformer.



a. VARIABLE AUTOTRANSFORMER

b. SCHEMATIC

Figure 13. Variable Autotransformer.

shaped core. A section of the wire is bare of insulation, and a movable carbon brush makes contact with it. This brush can be moved to different positions to change the transformer ratio. Variable autotransformers are often used in variable a.c. power supplies.

OTHER TRANSFORMERS

Many other types of transformers are in common use. Several are briefly described here.

All transformers discussed thus far deliver a constant output voltage with a constant input voltage. The output current varies with the load. Sometimes a constant output current is desired under changing load conditions. This can be accomplished with the constant current transformer shown in Figure 14. In the diagram, C is the transformer core, A is the primary coil, and B is the movable secondary coil, supported in part by a counterweight. Current flowing in the two coils sets up opposing magnetic fields that push them apart. As the secondary moves upward, flux leakage increases, and output voltage drops. Such transformers can deliver almost constant output current over a wide range of voltages. Constant current transformers are often used in large-scale series illumination systems.

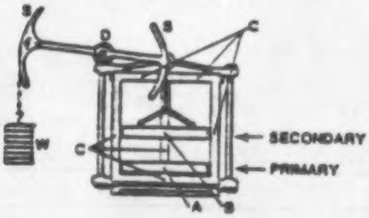


Figure 14. Constant Current Transformer.

Figure 15 shows the application of specialized instrument transformers for measuring current, voltage, and power in a.c. systems. These transformers are used when the voltages exceed a few thousand volts and for currents above about 20 A.

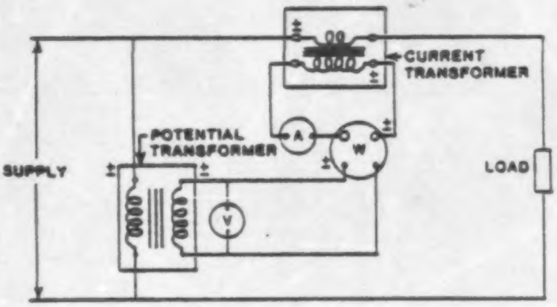
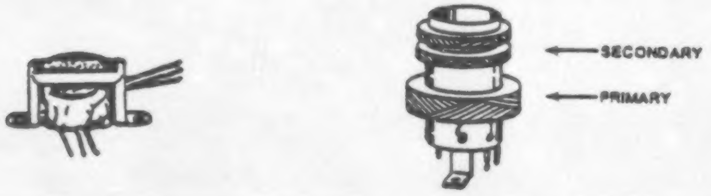


Figure 15. Connection of Instrument Transformers.

The voltage transformer reduces a large a.c. voltage to a level that can be measured conveniently with an a.c. voltmeter. The current transformer is a step-up transformer that increases voltage and greatly reduces current for easy measurement with an a.c. ammeter. A portable measuring device of this type, called an "amp-clamp," consists of a meter attached to the secondary coil of a transformer whose core is clamped around a single conductor of an a.c. power line. The power line acts as a single-turn primary.

The discussion thus far has applied only to transformers operating at a.c. power frequencies. Transformers are also employed as impedance matching devices in many circuits at higher frequencies. Figure 16a shows a small audio transformer used in an audio amplifier at frequencies up to about 25 kHz. Figure 16b is a radio frequency transformer, which has air cores because its operating frequency is so high that there is not sufficient time during one period of the wave for magnetic domains of a material to realign.



a. AUDIO TRANSFORMER

b. RADIO FREQUENCY TRANSFORMER

Figure 16. High-Frequency Transformers.

TROUBLESHOOTING TRANSFORMERS

Transformers are subject to two types of failure: open circuits and shorted windings.

An open circuit in a transformer winding occurs when the conductor has been broken through melting at high current or mechanical strain. This fault can be identified by measuring coil resistance with an ohmmeter. A good coil will show a short circuit.

An ohmmeter cannot be used to identify a shorted coil. When a short occurs, one or more loops of conductor are shorted together. The resistance of the coil may change very little, and the transformer may continue to supply a lowered output voltage for a short time. However, the shorted loop acts as a shorted secondary of the transformer. High currents produced in this loop cause the transformer to overheat and "burn up."

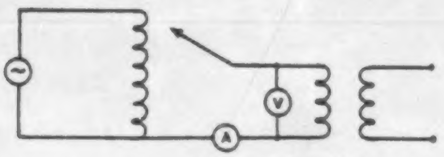


Figure 17. Testing a Transformer.

A shorted coil can be identified using the circuit shown in Figure 17. When high-voltage transformers are tested in this manner, the primary is chosen as the low voltage side of the transformer. The secondary of the transformer is open, and the input voltage is increased slowly from zero to the operating voltage with a variable autotransformer. The primary current at the rated value should not exceed a few percent of the rated primary current. If it does, part of one of the coils is shorted.

Transformer failure, due to overcurrent, often indicates a short in the transformer load. When transformer failure occurs, the entire circuit should be checked to locate any other problems. Replacement transformers should always be chosen to match circuit parameters. Operating a transformer above its rated values decreases efficiency and results in overheating. Operation at a small fraction of the rated values results in lowered efficiency.

EXERCISES

1. A transformer has an input voltage of 7200 V, an input current of 2.5 A, and an output voltage of 230 V. Determine the output current.
2. A transformer is rated as primary voltage 115/230 V, secondary voltage 24/48 V, secondary current 4/2 A. Draw diagrams showing the four

possible connections of this transformer, and label input and output currents and voltages on each diagram.

3. Three identical single-phase transformers with a turn ratio of 2.3 are used as a step-down, three-phase transformer. The line-to-line input voltage is 250 V, and the current is 25 A. Determine the output current and line-to-line voltage for the following connections:
   a. Δ-Δ
   b. Δ-Y
   c. Y-Δ
4. Read the Laboratory Procedures section of this module. Then write a set of step-by-step instructions for measuring the efficiency of the autotransformer used in the lab as a function of output voltage.
5. A transformer rated primary 115/230 V, secondary 230/460 A is suspected of failure. Explain how this transformer can be checked for open and shorted coils. Include the specifications of the equipment necessary for the tests.

LABORATORY MATERIALS

Two VOMs
a.c. wattmeter,   W, 115 a.c., 1 A, Simpson model 79
0.20 kVA variable autotransformer, input 120 V a.c., output 132 V a.c., 1.5 A, with male quick-disconnect terminals, mounted on open stand
Power transformer, primary 115/230 V a.c., secondary 12/24 V a.c., secondary current 4/2 A, with male quick-disconnect terminals, mounted on board
Two power resistors, 12 ohm, 25 W, with male quick-disconnect terminals, mounted on board
a.c. power cord with female quick-disconnect terminals and connecting wires with female quick-disconnect terminals
d.c. power supply. 0-12 V d.c., 1 A

LABORATORY PROCEDURES

1. Using the test procedure presented in the Subject Matter and the ohmmeter function of the VOM, check the continuity of the windings of both the power transformer and the autotransformer.
2. Connect the circuit shown in Figure 18 for accurately determining the resistance of the power resistors. The voltmeter is a VOM set to measure 0-10 V d.c. The ammeter is a VOM set to measure 0-500 mA d.c.

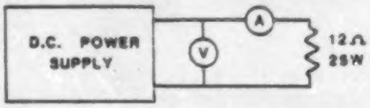


Figure 18. Determining Resistance of Power Resistor.

3. Turn on the power supply and adjust the current through the power resistor to 500 mA. Measure and record resistor voltage and current in the Data Table, and calculate the actual resistance. This value of resistance will be used in future calculations.
4. Turn off the power supply, replace the first resistor with the second, and repeat Step 3.
5. Connect the circuit shown in Figure 19, but do not connect the power resistor yet. V_1 is a VOM set to measure 0-250 V a.c. V_2 is a VOM set to measure 0-50 V a.c. Transformer secondaries are connected in series. CAUTION: BEWARE OF EXPOSED TERMINALS. HAZARDOUS VOLTAGES WILL BE PRESENT WHENEVER CORD IS PLUGGED IN.

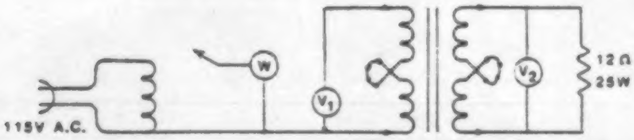


Figure 19. Experimental Setup.

6. Set the variable autotransformer for an output voltage of zero volts and plug the power cord into a 115-V a.c. outlet.

7. Check the transformer for shorted windings by slowly increasing the input voltage to 115 V a.c. If the wattmeter indicates a power consumption of more than a fraction of a watt, the transformer contains a shorted coil.
8. Return the input voltage to zero. Disconnect the autotransformer from the power source, connect the power resistor as shown in Figure 19, and reconnect the power source.
9. Set the variable transformer for an input voltage of 25 V a.c. to the power transformer as measured on V_1.
10. Record input voltage and power and output voltage of the power transformer in the Data Table.
11. Increase the input voltage of the power transformer in 25-volt steps, repeating Step 10 each time, until an input voltage of 125 V a.c. is reached. Unplug the power cord when all data has been taken.
12. Record the resistance of the power resistor in the Data Table.
13. Calculate the output power of the transformer, using –

$$P = \frac{V^2}{R} .$$

Calculate the efficiency of the percent transformer, using –

$$\text{Efficiency (\%)} = \frac{\text{Output Power}}{\text{Input Power}} \times 100.$$

14. Reconnect the transformer secondaries in parallel, as shown in Figure 20. Set V_2 to measure 0-10 V a.c. Connect the second power resistor in parallel with the first.

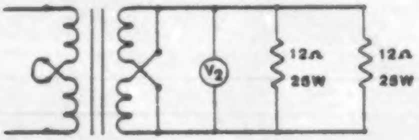


Figure 20. Parallel Connection of Transformer Secondaries.

15. Calculate the load resistance of the circuit, using –

$$R_L = \frac{R_1 R_2}{R_1 + R_2} \text{ .}$$

Record this value in the Data Table.

16. Repeat Steps 9 through 13 for this transformer connection.

17. On a single sheet of graph paper, plot transformer efficiency versus input power for the series connection and the parallel connection.

DATA TABLE

DATA TABLE.

Resistor	Current (A)	Voltage (V)	Resistance (Ω)
1			
2			

SECONDARIES IN SERIES

Input Voltage (V)	Input Power (W)	Output Voltage (V)	Circuit Resistance (Ω)	Output Power (W)	Efficiency (%)
25					
50					
75					
100					
125					

SECONDARIES IN PARALLEL

Input Voltage (V)	Input Power (W)	Output Voltage (V)	Circuit Resistance (Ω)	Output Power (W)	Efficiency (%)
25					
50					
75					
100					
125					

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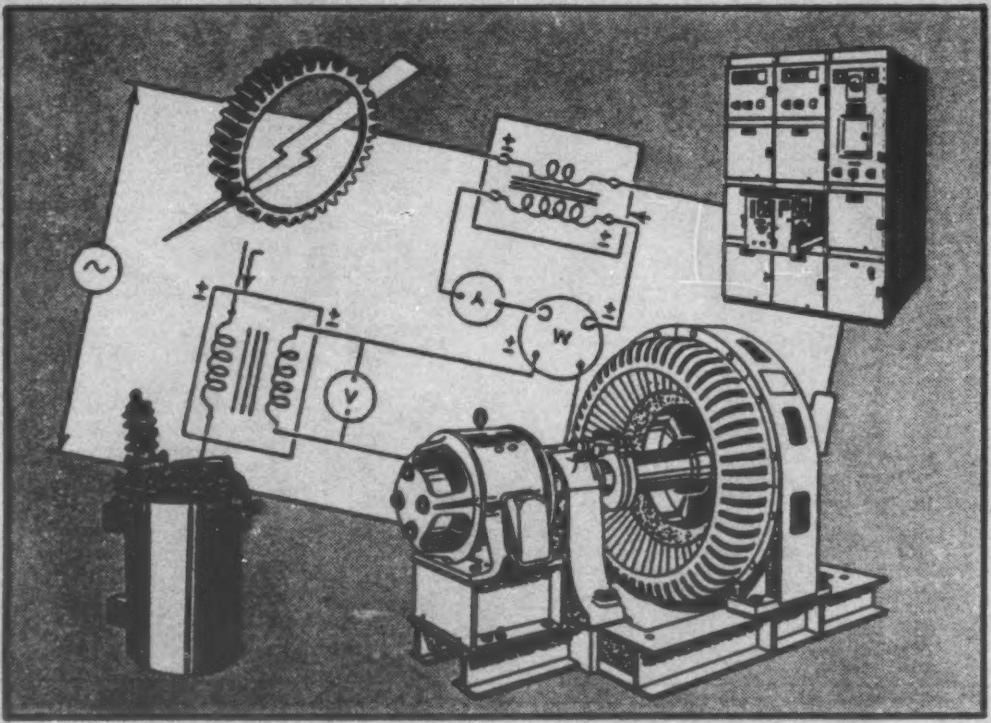

MODULE EM-04

GENERATORS AND ALTERNATORS

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Generators and alternators are electromechanical devices that convert input mechanical energy to output electrical energy. A generator produces a d.c. output voltage. It consists of a coil of wire rotating in a fixed magnetic field. An alternator produces an a.c. output voltage. It consists of a rotating magnet surrounded by fixed coils.

This module discusses the basic theory and design of generators and alternators. The construction details and output characteristics of several types are included. Other topics discussed are loss factors and efficiency, output voltage control, and parallel connection of both d.c. generators and alternators. In the laboratory, the student will measure the output characteristics of a generator and an alternator.

PREREQUISITES

The student should have completed Module EM-01 of "Electromechanical Devices."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Draw and label a diagram of a simple d.c. generator and a simple alternator.
2. State the three factors that determine the output voltage of the following:
   a. A d.c. generator
   b. An alternator
3. Identify the following components as laminated or not laminated and state the reasons for the construction in each:
   a. A d.c. generator stator
   b. A d.c. generator rotor
   c. An alternator stator
   d. An alternator rotor

4. Explain how d.c. generators and alternators are connected to external circuits and how this affects the size of brushes used in each.
5. Draw and label diagrams showing the following d.c. generator connections:
   a. Shunt
   b. Series
   c. Separately-excited
   d. Compound
6. Draw and label a diagram showing output voltage versus load current for a shunt generator and a compound generator. Explain how the series coil produces the difference in the two curves.
7. Draw and label a diagram showing output voltage versus load current for a compound generator with the series field opposing the shunt field. State an application for this type of generator.
8. Draw and label a diagram showing two methods of controlling the output voltage of a d.c. generator. Explain each method.
9. Explain the role residual magnetism plays in starting a d.c. generator.
10. Explain the four steps necessary for transferring an electrical load from one generator to another without intercepting the electrical power in the load.
11. Given any two of the following quantities concerning an alternator, determine the other two:
    a. Number of pole pairs on the rotor
    b. Rotational rate
    c. Output frequency
12. Draw and label diagrams showing the coil connections and the output waveform of a three-phase alternator.
13. Given the number of pole pairs on the rotor of a three-phase alternator, determine the total number of armature coils and explain how they are connected.
14. Draw and label a diagram showing the mounting of alternator armature bars in the stator core teeth.
15. Draw and label a diagram of a brushless exciter used in large a.c. generating stations and explain how it works.
16. List the additional requirement that must be met when paralleling alternators beyond those necessary for d.c. generators.

17. Given the appropriate equipment, operate a d.c. generator and an alternator and determine their operating characteristics.

THE SIMPLE D.C. GENERATOR

Figure 1 shows the basic components of a simple d.c. generator. This device consists of a square loop of wire that is rotated inside a fixed magnetic field. Each end of the wire loop is connected to one-half of a split-ring conductor. Brushes connect the output voltage from the split ring to an external circuit.

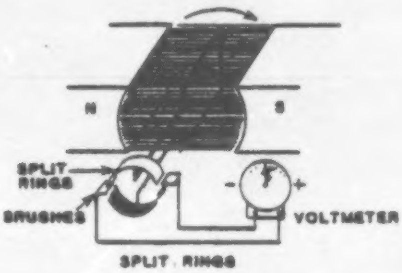

Figure 1. Simple d.c. Generator.

The operation of this device is illustrated in Figure 2. In Figure 2a, the coil is just rotating past the vertical position. Wire segment A is moving to the right, and wire segment B is moving to the left. Since both segments are moving in the direction of the magnetic field lines, there is no induced voltage.

In Figure 2b, the rotation has continued. Wire segment A is moving upward through the magnetic field, and wire segment B is moving downward. Both segments cut the fixed magnetic field lines to produce forces on electrons in the directions shown in the figure. These forces produce an output voltage on the brushes.

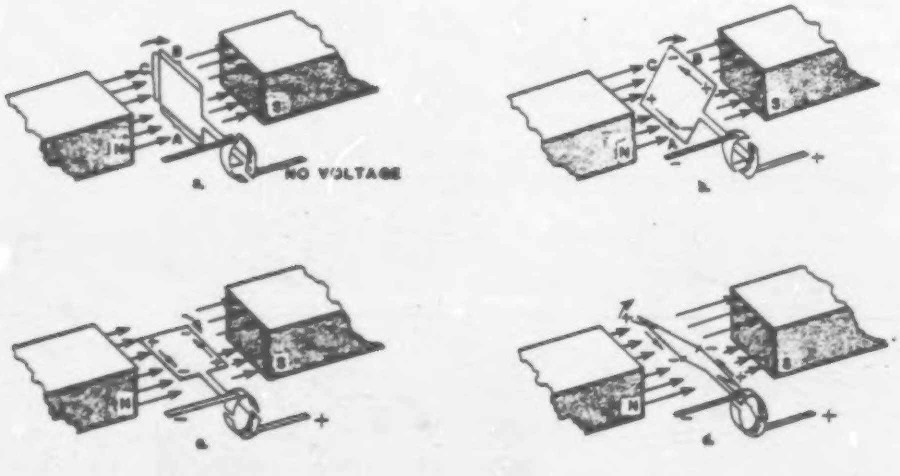

Figure 2. Operation of the Simple d.c. Generator.

In Figure 2c, the coil has rotated into a plane parallel with the applied magnetic field. At this time, wire segments A and B move perpendicular to the magnetic field, producing the maximum output voltage.

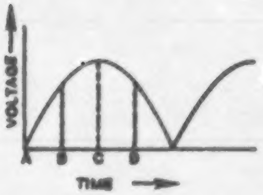

Figure 3. Output of Simple d.c. Generator.

In Figure 2d, rotation has continued and the output voltage is dropping from its maximum value. When the coil reaches the vertical position, the output voltage will again be zero. Each brush will slip to the other half of the split ring, and the process will be repeated. Figure 3 shows the output waveform of the simple d.c. generator. The points labeled a, b, c, and d correspond to the lettered drawings in Figure 2.

The rotating coils in most generators consist of several loops of wire, as shown in Figure 4. The maximum output voltage of such a generator depends on the following factors:

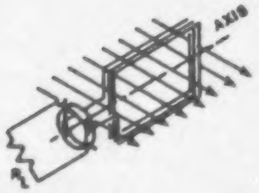

Figure 4. Multi-Turn Generator Coil.

- Number of loops in the moving coil
- Strength of the magnetic field
- Rotational rate of the coil

Increasing any one of these quantities will increase the output voltage.

Figure 5a shows an improved generator design consisting of two coils of wire connected to a commutator with four segments. Each coil is in contact with the brushes only during the part of the rotational cycle that produces the maximum output voltage. This produces the smoother output shown in Figure 5b.

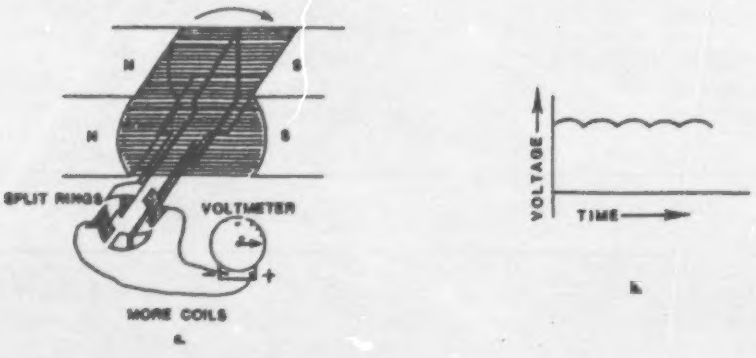

Figure 5. Improved d.c. Generator.

CONSTRUCTION OF D.C. GENERATORS

Figure 6 shows the construction of the commutator of a d.c. generator. The commutator segments are made of copper. Carbon brushes are held in contact with the commutator segments by spring tension. The brushes and commutator segments of a d.c. generator must be capable of carrying the output current of the generator.

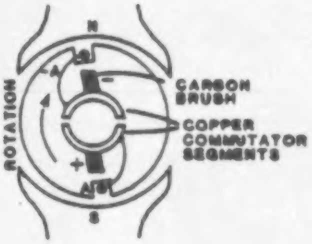

Figure 6. Commutator of d.c. Generator.

Figure 6 shows only a single coil on the armature, but several coils are usually used. Sometimes they are connected to individual commutator segments, as shown in Figure 5a; but more often they are interconnected, as shown in Figure 7, which is a schematic diagram of the rotor of a generator with 12 rotor coils designed to be used in a two-pole stator (fixed) field. The coils are wires in series, so the output voltage is the sum of the voltages on all the coils. This arrangement smoothes the output voltage further.

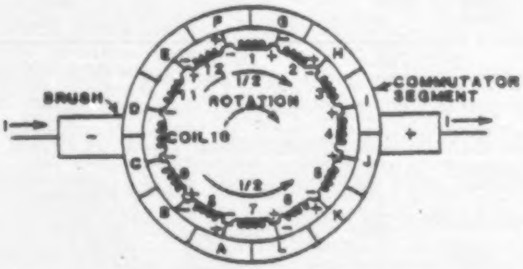

Figure 7. Schematic Diagram of Armature Winding for Two-Pole Machine.

The rotor of a d.c. generator consists of a stack of laminated core elements coated with varnish to provide electrical insulation of each element. If the rotor was constructed of a single piece of metal, the same magnetic induction that produces current in the coils would produce large eddy currents in the rotor. Laminating the rotor greatly reduces power losses due to eddy currents.

The assembled rotor core contains grooves along its length to accept the armature windings, as shown in the automotive generator in Figure 8. This allows the magnetically permeable material of the core to extend above the conductors, reducing the air gap between the core of the rotator and the core of the stator. This air gap should be as small as possible to increase the magnetic coupling between the fixed field and the rotating core.

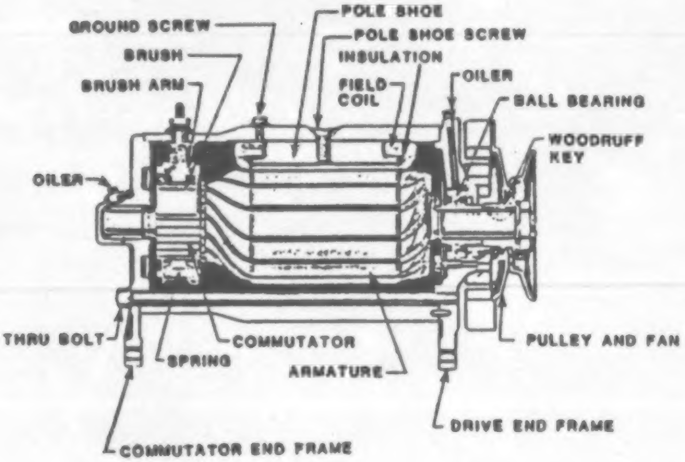
GROUND SCREW
BRUSH
BRUSH ARM
OILER
POLE SHOE
POLE SHOE SCREW
INSULATION
FIELD COIL
OILER
BALL BEARING
WOODRUFF KEY
THRU BOLT
SPRING
COMMUTATOR
ARMATURE
PULLEY AND FAN
DRIVE END FRAME
COMMUTATOR END FRAME

Figure 8. Cutaway View of an Automotive d.c. Generator.

The fixed magnetic fields of all d.c. generators — except the very smallest models — are supplied by current flow through field coils wound around the magnetically permeable stator, also called the "frame" or "yoke." This frame includes pole shoes that distribute the magnetic field through the armature, as shown in Figure 9. The generator frame is usually cast in a single piece or in several large pieces. Since it carries a constant magnetic field, it has no induced eddy currents, and lamination is unnecessary. Figure 10 is a cross-section diagram of a four-pole d.c. generator. The armature windings are not shown, but they are located in the slots in the laminated armature core. Figure 11 shows a large six-pole d.c. generator.

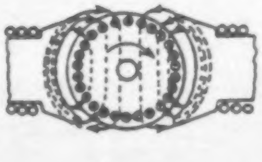

Figure 9. Distribution of Magnetic Field by Pole Shoes.

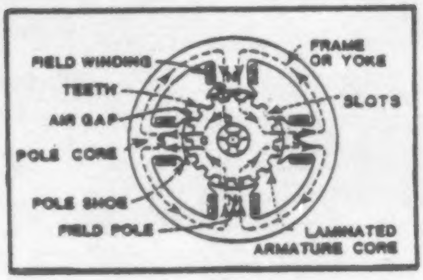
FIELD WINDING
TEETH
AIR GAP
POLE CORE
POLE SHOE
FIELD POLE
FRAME OR YOKE
SLOTS
LAMINATED ARMATURE CORE

Figure 10. Four-Pole d.c. Generator.

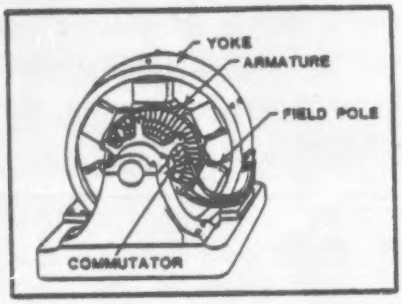
YOKE
ARMATURE
FIELD POLE
COMMUTATOR

Figure 11. Large d.c. Generator.

FIELD COIL CONNECTIONS IN D.C. GENERATORS

The current for the field coils of a d.c. generator may be supplied by the three connections shown in Figure 12. In the shunt connection, a portion of the output current of the generator passes through field coils connected in parallel with the generator output. The field current at a fixed voltage is limited only by the resistance of the coils. Shunt coils consist of many turns of relatively small wire and usually carry a current of 3-5% of the generator output current. Most small d.c. generators are the shunt type.

In the series-connected generator, all of the output current passes through the field coils before leaving the generator. Since induced voltage depends on field strength, and field strength depends on field coil current, the output voltage of a series-connected generator depends on the electrical load to which it is connected. Higher load resistance produces lower current and lower output voltage. Thus, pure series generators are seldom used.

In the separately-excited generator, the current for the field coils is provided by an external d.c. source. The output voltage of the generator can be varied by changing the externally-applied field current.

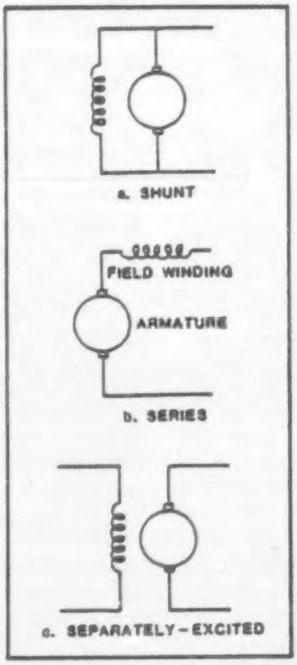
a. SHUNT
FIELD WINDING
ARMATURE
b. SERIES
c. SEPARATELY-EXCITED

Figure 12. Three d.c. Generator Connections.

Most large d.c. generators are the compound type, as shown in Figure 13. The compound generator has both shunt and series coils. The reason for this is illustrated by the output voltage versus load curves shown in Figure 14.

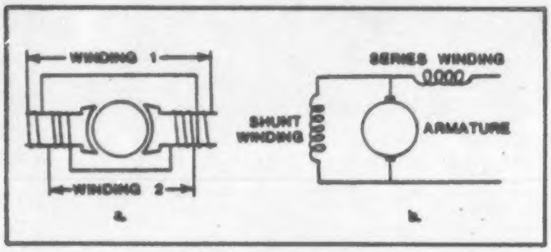

Figure 13. Compound Generator Connections.

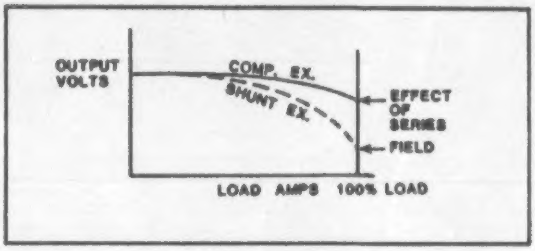

Figure 14. Generator Output Characteristics.

In the shunt-connected generator, an increased output current causes a greater voltage drop across the rotor windings. This reduces the output voltage. The lowered output voltage results in lower field coil current, which lowers output voltage even further.

The compound generator is designed to compensate for this voltage "droop." A low-resistance series winding carries the output current of the generator. This coil is wound so its magnetic field adds to the field of the shunt coils. At higher currents, the increased field of the series coil compensates for the reduced field of the shunt coils.

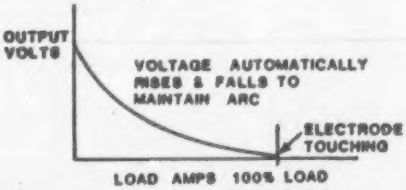

Figure 15. Arc Welder Generator.

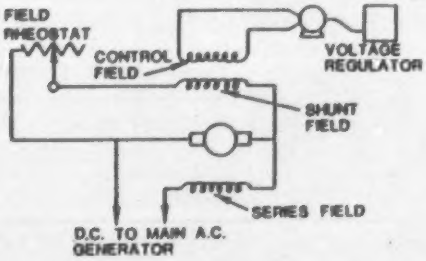

Figure 16. Control Field and Voltage Regulator.

If the series coil is connected with its field opposing the field of the shunt coil, an increase in output current greatly reduces output voltage. This is commonly done in d.c. generators used for arc welding. The output curve of such a generator is shown in Figure 15. Many applications of large d.c. generators require that the output voltage remain constant under varying load conditions and that the voltage can be adjusted as desired. Figure 16 is a schematic of such a system. A rheostat (variable resistor) is connected in series with the shunt coil. Changing this resistance changes the shunt field current and controls the output voltage. The same effect can be achieved with an externally-excited coil. The generator in Figure 16 has a rheostat for changing the output voltage and an externally-excited coil controlled by a voltage regulator. This coil keeps the output voltage constant at the desired setting and can compensate for abrupt, large changes in load.

OPERATION OF D.C. GENERATORS

The first time a new generator is operated, an externally-excited current must be supplied to the shunt coils to begin generator action. Once a current flows in the coils, the external source may be disconnected, and the generator will continue to supply its own field current. On future operation of the generator, no external current source is required. The residual magnetism of the stator core is sufficient to generate a small voltage in the rotating armature coils. This voltage produces a small current flow in the shunt coils, thus increasing the field strength and the generated voltage. The generator output voltage quickly reaches the rated value. All that is required to turn on a d.c. generator is to connect it to a source of rotary mechanical power.

Most generators are designed to operate at a constant rotational rate. Thus, their source of mechanical power (gasoline engine, turbine, a.c. motor, etc.) is regulated to operate at a constant speed under varying loads. The output voltage of a generator rotating at a constant speed depends upon the current through its field coils. The output power of the generator is the product of the output current and voltage. At a constant rotational rate and output voltage, an increase in output current must be accompanied by a proportional increase in input mechanical torque. Thus, the output electrical power of a generator is dependent upon the mechanical input power.

A d.c. generator can be turned off simply by removing the mechanical input power and allowing it to coast to a stop without disconnecting it from the external circuit; however, in some cases, the generator must be disconnected from the circuit while it continues to rotate. If the load is disconnected abruptly, the inductive kick of the generator will produce high voltages and arcing. This can be prevented by the use of a discharge resistor. This resistor is connected across the generator output just before the external circuit is disconnected. The inductive kick then produces only a current surge through the discharge resistor, and no arcing occurs.

When two generators are operated in parallel or when a load circuit is transmitted from one generator to another, precautions must be taken to avoid generator damage. The following procedure will assure safe operation. The entire load is initially supplied by generator 1 and is to be transferred to generator 2.

1. With generator 2 disconnected from the load circuit, bring it to its desired rotational rate and adjust its output voltage to slightly above that of generator 1.
2. Connect generator 2 in parallel with generator 1. The electrical load will be shared by the two generators in a ratio equal to the ratio of their mechanical input powers. Parallel operation may be continued as long as desired.
3. Decrease the field current of generator 2 until most of the load is supplied by generator 2.
4. Disconnect generator 1, using the discharge resistor method described previously. Generator 2 now supplies the entire electrical load. Under no circumstances should a generator be disconnected from its mechanical input power while connected in parallel with another generator. If this is done, the disconnected generator acts as an electrical motor with no load. This can produce excessive currents and rotational rates that will damage the generator.

THE ALTERNATOR

Figure 17 shows the basic components of a simple alternator. It consists of a cylindrical magnet rotating inside a stationary coil of wire. The output voltage and current is produced as the rotating magnetic field lines cross the fixed conductors. Thus, the alternator requires no brushes and commutator to connect to an external circuit.

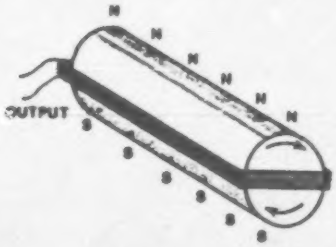

Figure 17.
Simple Alternator.

Figure 18 shows the generation of a single period of the a.c. output voltage as the simple alternator rotates through one complete revolution.

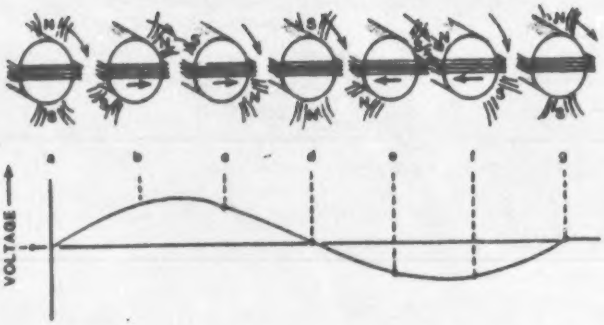

Figure 18. Generation of an a.c. Wave.

The output voltage of the alternator depends on the following quantities:

- Number of loops in the stationary coil
- Strength of the rotating magnetic field
- Rotational rate of the magnetic field

The magnetic field in practical alternators is supplied by a d.c. current flowing through coils of wire in the rotor. The coil is connected to an external current source by means of brushes and continuous slip rings. In most cases, the rotor will have multiple poles, and the static armature will contain one coil for each pole pair. Figure 19 shows an alternator with three pole pairs. The armature windings of this alternator consist of three coils wound in the slots in the stator. Each of the three pole pairs produces a current in one of the three coils at the same time; thus, the a.c. voltages of the coils are in phase. The coils are connected in series, and their voltages add to produce the output voltage. The output frequency of the alternator is the rotor rotational rate (in revolutions per second) multiplied by the number of pole pairs and matching armature coils. Thus, an alternator with six pole pairs, rotating at 10 revolutions per second, produces a frequency of 60 Hz.

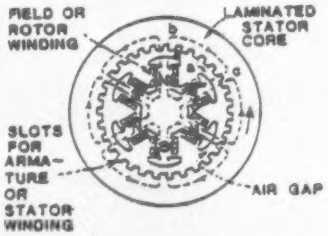

Figure 19. Six-Pole Alternator.

The alternators discussed thus far are single-phase alternators. Most alternators produce a three-phase output; that is, they produce three identical voltage waves on three pairs of output terminals. This is accomplished

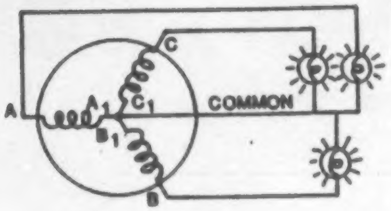
C
A
A1
C1
COMMON
B1
B

Figure 20. Three Coils with Common Return.

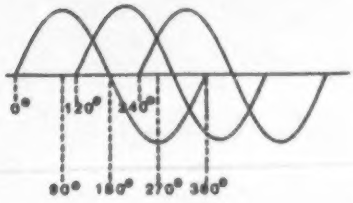

Figure 21. Three-Phase Output Waves.

by adding two additional sets of armature windings at intervals of 120° around the stator frame. The armature then consists of three sets of coils 120° apart. Each set contains the same number of coils as there are pole pairs on the rotor.

Figure 20 shows the electrical connections of the armature coils of a three-phase alternator. Each coil shown in the diagram represents one set of coils in the alternator armature. The output waveform of this alternator is shown in Figure 21. The first wave is the voltage between A and A_1, the second wave is the voltage between B and B_1, and the third is that between C and C_1. Points A_1, B_1, and C_1 are connected and form the common return line for each of the alternator phases.

AUTOMOBILE ALTERNATORS

One of the most common applications of small alternators is in the generation of electrical power in automobiles. Figure 22 shows the construction of the rotor of such an alternator. The magnetic field is produced by a d.c. current flowing through a single coil wound around the rotor shaft. This coil is connected to an external d.c. source by a pair of slip rings and brushes. The poles of the rotor are formed by the interlocking fingers of

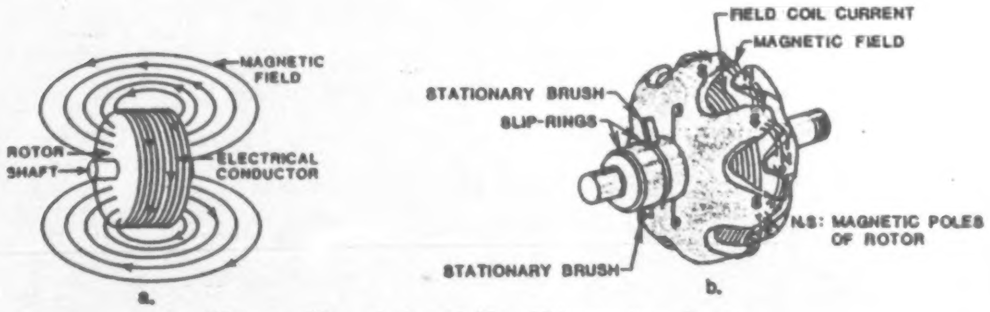
MAGNETIC FIELD
ROTOR SHAFT
ELECTRICAL CONDUCTOR
a.
FIELD COIL CURRENT
MAGNETIC FIELD
STATIONARY BRUSH
SLIP-RINGS
N.S: MAGNETIC POLES OF ROTOR
STATIONARY BRUSH
b.

Figure 22. Automobile Alternator Rotor.

two iron shell halves. Each shell half contains one finger for each pole pair. Figure 23 shows the construction of the stator of the alternator. Figure 23a shows seven field coils connected in series to match the seven pole pairs of the rotor. This set of windings produces one of the output phases.

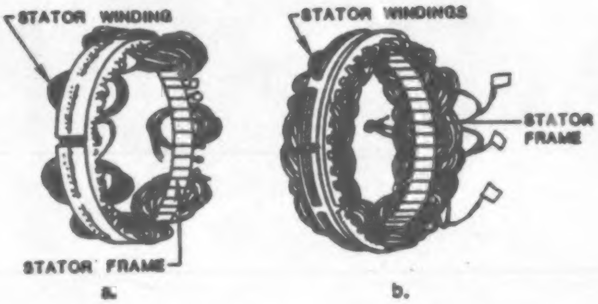
STATOR WINDING
STATOR FRAME
a.
STATOR WINDINGS
STATOR FRAME
b.

Figure 23. Automobile Alternator Stator.

In Figure 23b, the other two sets of coils have been added to the stator frame and connected electrically, as shown previously in Figure 20.

Figure 24 is an exploded view of the completed alternator. The alternator is connected to the internal rectifier circuit shown in Figure 25 to produce a d.c. output. The output voltage of the alternator is regulated by regulating the d.c. current in the rotor.

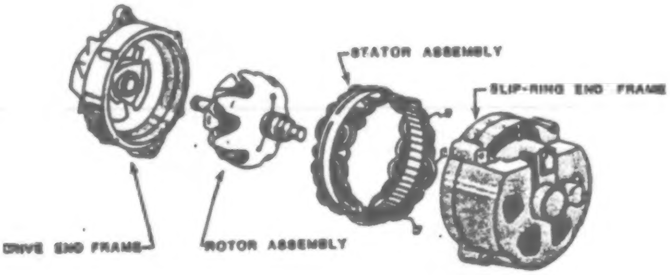
STATOR ASSEMBLY
SLIP-RING END FRAME
DRIVE END FRAME
ROTOR ASSEMBLY

Figure 24. Exploded View of Automobile Alternator.

In an alternator, the magnetic field of the rotor is produced by d.c. current flow and does not change direction. Thus, no eddy currents can be induced, and the rotor need not be laminated. The stator frame, however, is subjected to alternating magnetic fields and must be of laminated construction to reduce induced eddy currents.

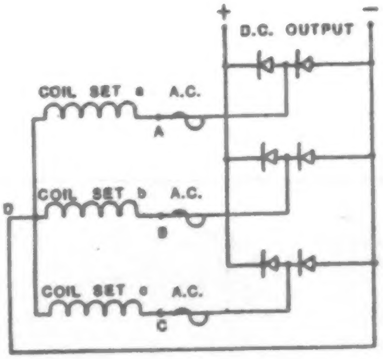
+
−
D.C. OUTPUT
COIL SET a
A.C.
A
COIL SET b
A.C.
B
D
COIL SET c
A.C.
C

Figure 25. Alternator Rectifier Circuit.

LARGE ALTERNATORS

Large alternators used for electrical power production have the same basic design as the automotibe alternator. Figure 26 shows the rotor of such an alternator. The rotor coils consist of rectangular copper bars set in slots along the sides of the solid steel rotor. The bars are wedged into place and held by steel retaining rings at each end. They are connected electrically to the copper rings at one end of the rotor. Large brushes contact these rings to supply the d.c. current to the rotor.

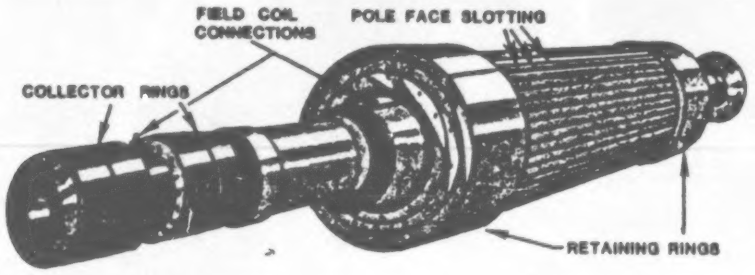

Figure 26. Rotor of Large Alternator.

The stator windings of the alternator are composed of copper bars constructed as shown in Figure 27. The individual copper strips are "transposed" along the length of the bar. Otherwise, unequal voltages due to unequal slot depth would produce eddy currents in the bars. The bar is covered with insulating tape. Such a bar-type winding is called an "armature" winding, taking its name from the copper bar armor worn by knights of medieval times.

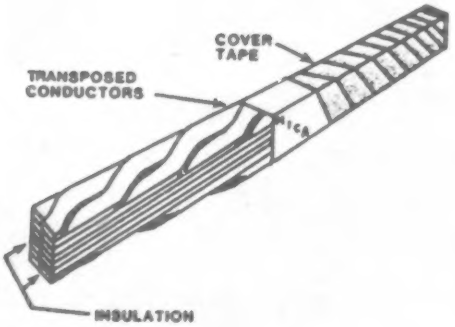

Figure 27. Stator Winding Bar.

Figure 28 shows the armature bar in place in the stator frame. The bars are held in place by non-magnetic wedges that fit between the core teeth. The cores of large alternators also contain cooling slots, through which water or a gas may pass to cool the stator. In some cases, the copper bars themselves are hollow and carry a coolant. The rotors of large alternators are electrically isolated from the stator frame to prevent the flow of eddy currents through a loop formed by the rotor and stator.

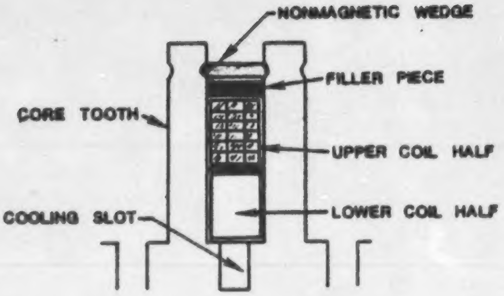
NONMAGNETIC WEDGE
FILLER PIECE
CORE TOOTH
UPPER COIL HALF
COOLING SLOT
LOWER COIL HALF

Figure 28. Cross Section of Slot.

Unlike d.c. generators, alternators cannot be connected to supply their own field current. The current in the alternator rotor must come from some source other than the alternator itself. This d.c. source is called an "exciter." Figure 29 shows one common way of exciting a large alternator. The initial power to start the exciter motor comes from an external source, such as another alternator. Once the exciter and the main a.c. generator (alternator) are both in operation, the exciter motor can be connected to the output of the a.c. generator. In this way, the alternator supplies its excitation current through an intermediate step of d.c. generation.

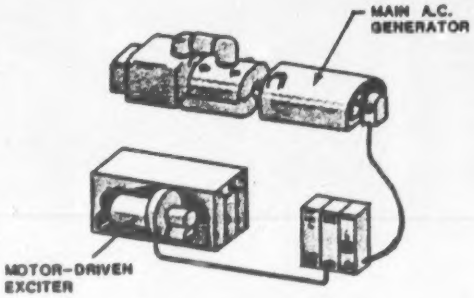
MAIN A.C. GENERATOR
MOTOR-DRIVEN EXCITER

Figure 29. Separately-Driven Exciter.

Figure 30 shows another arrangement commonly used in large electrical plants. A permanent magnet alternator, an excitation alternator, a rectifier assembly, and the main a.c. generator are all connected on a single shaft. The output of the permanent magnet alternator is amplified and rectified and is used as the excitation current through the stationary field coils of the excitation alternator. An a.c. current is produced in the rotating coils of the excitation alternator. This current is rectified

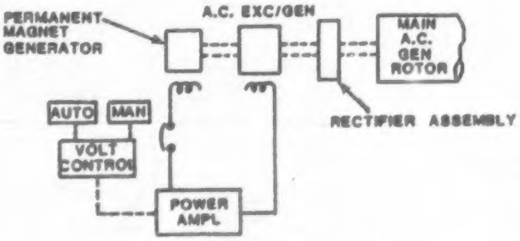
PERMANENT MAGNET GENERATOR
A.C. EXC/GEN
MAIN A.C. GEN ROTOR
RECTIFIER ASSEMBLY
AUTO
MAN
VOLT CONTROL
POWER AMPL

Figure 30. Brushless Excitation System.

by a rectifier assembly located on the rotating shaft and fed to the rotating coils of the main alternator. This type of excitation system has the advantage of containing no brushes.

OPERATION OF ALTERNATORS

An alternator can be placed in service by bringing its rotational rate to the specified value and then supplying the field current necessary to produce the desired output voltage. The output voltage of the alternator is regulated by regulating the field current. This is often accomplished by a voltage regulator that monitors alternator a.c. output and controls the d.c. field current. Such regulators are often designed for operation at a fixed output frequency. For this reason, current should not be supplied to the alternator rotor at low rotational rates. This could damage the voltage regulator circuits. Like the d.c. generator, the total output power of an alternator is dependent upon the total mechanical input power.

Alternators can be placed in parallel operation by a process similar to that used for d.c. generators. The additional requirements necessary before the parallel connection is made are that both alternators have the same output frequency and that their outputs are in phase at the instant the switch is closed. The alternators will then be locked in phase with one another and will share the electrical load in a ratio equal to the ratio of their mechanical input powers. Alternators are reversed from a parallel connection in the same manner as d.c. generators.

MAINTENANCE

The maintenance procedures for generators and alternators are the same as those for electric motors discussed in Module EM-05, "D.C. Motors." Discussions of motor power losses and efficiency in that module also apply to generators and alternators.

EXERCISES

1. An alternator with four pole pairs is used to produce a 60-Hz a.c. voltage. What is its rotational rate?
2. The d.c. generator in Figure 16 is connected to a constant resistive electrical load and a source of mechanical input energy that has a constant rotational rate and changes its input energy to meet the demands of the generator. Explain what happens to each of the following quantities when the rheostat controlling the shunt coil current is changed from a higher resistance to a lower resistance:
   a. Shunt coil current
   b. Output voltage
   c. Output current
   d. Mechanical input power
3. Why is a discharge resistor necessary when a large d.c. generator is disconnected from an electrical load? Explain how this resistor is used.
4. What happens if a d.c. generator, operating in parallel with a second generator, is suddenly disconnected from its source of mechanical input power?
5. A three-phase alternator has 15 coils on its stator. How are they connected and how many pole pairs must the rotor have?
6. An a.c. electrical load is to be transferred from one alternator to another without interrupting the current flow. Explain, step by step, how this can be accomplished.

LABORATORY MATERIALS

12-volt compound d.c. generator
Automobile alternator
Constant speed electric motor
Mechanical couplings and mounts for connecting electric motor to generator and alternator
12-V d.c. power supply
10 kΩ, 5-W variable resistor (potentiometer)
d.c. voltmeter, 0-25 V

d.c. ammeter, 0-5 A
d.c. milliammeter, 0-250 mA
Five 12Ω, 12-W power resistors
Five SPST switches

Note: A compound d.c. motor can be used as a d.c. generator. If this is done, all internal coil connections should be disconnected and coil leads brought out of the motor. The size of the power resistors used as a load and the shunt rheostat must be scaled to the motor ratings.

LABORATORY PROCEDURES

1. Connect the d.c. generator mechanically to the driving motor. With all generator coils disconnected, turn on the driving motor momentarily and verify mechanical operation of the motor-generator combination.
2. Connect the generator as shown in Figure 31. The circuit to the right of the output terminals will be used as the output circuit for all parts of this laboratory.

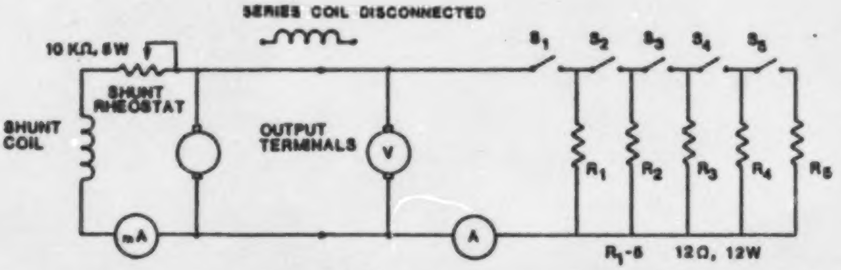

Figure 31. Shunt-Connected Generator.

3. Set shunt coil rheostat for maximum series resistance. Open S_1 through S_5.
4. Turn on the driving motor and observe the output voltages. Set the shunt rheostat to produce an output voltage of 12 V. Record the shunt coil current and output voltage in Data Table 1.
5. Divide the recorded value of shunt coil current by 5. Reduce the current by this amount with the rheostat, and record the new shunt coil current and output voltage.

6. Continue to reduce the shunt coil current in equal steps until the minimum current is reached, recording the current and output voltage each time.
7. Return the shunt coil current to the value necessary to produce a 12-V output voltage.
8. Add the load resistors to the circuit one at a time by closing S_1 through S_5 in order. Record the output current and output voltage in Data Table 1 after each switch is closed. Do not change shunt coil rheostat setting.
9. Turn off the driving motor and allow the generator to coast to a stop. Open S_1 through S_5.
10. Calculate output power by multiplying output voltage and output current for each load, and record in Data Table 1.
11. Connect the generator as shown in Figure 32, and repeat Steps 7 through 10.

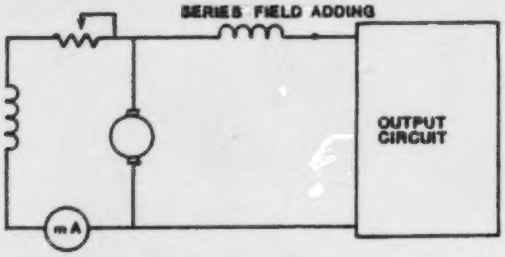

Figure 32. Compound Generator with Fields Adding.

12. Reverse the connections of the series field coil of the generator so its magnetic field will oppose that of the shunt coil, and repeat Steps 7 through 10.
13. Replace the d.c. generator with the alternator. With all alternator coils disconnected, turn on the driving motor momentarily and verify mechanical operation of the motor-alternator combination.
14. Connect the alternator as shown in Figure 33.
15. Repeat Steps 3 through 10 for the alternator, recording values in Data Table 2. In this case, the rheostat controls the externally-applied current through the alternator rotor.
16. Draw graphs of output voltage versus field current for the d.c. generator and the alternator.

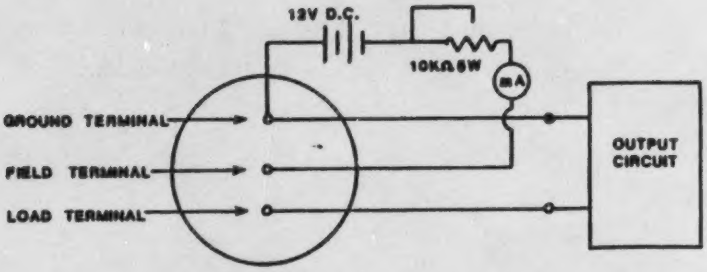
12V D.C.
10KΩ 5W
mA
GROUND TERMINAL
FIELD TERMINAL
LOAD TERMINAL
OUTPUT CIRCUIT

Figure 33. Alternator Connections.

17. Draw four graphs of output voltage versus output current on the same sheet of graph paper. Label the graphs as follows:
    a. Shunt generator
    b. Compound generator with fields adding
    c. Compound generator with fields opposing
    d. Alternator
18. Compare the graphs and explain the reasons for the shape of each curve.

DATA TABLES

DATA TABLE 1. D.C. GENERATOR.

<table>
<tr><td colspan="6">OUTPUT VOLTAGES VERSUS SHUNT COIL CURRENT</td></tr>
<tr><td>Shunt coil current (mA)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Output voltage (V)</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

<table>
<tr><td colspan="4">SHUNT-CONNECTED GENERATOR</td></tr>
<tr><td>Load Resistors (number)</td><td>Output Voltage (V)</td><td>Output Current (A)</td><td>Output Power (W)</td></tr>
<tr><td>0</td><td></td><td></td><td></td></tr>
<tr><td>1</td><td></td><td></td><td></td></tr>
<tr><td>2</td><td></td><td></td><td></td></tr>
<tr><td>3</td><td></td><td></td><td></td></tr>
<tr><td>4</td><td></td><td></td><td></td></tr>
<tr><td>5</td><td></td><td></td><td></td></tr>
</table>

Data Table 1. Continued.

COMPOUND GENERATOR WITH FIELD COILS ADDING			
Load Resistors (number)	Output Voltage (V)	Output Current (A)	Output Power (W)
0			
1			
2			
3			
4			
5			

COMPOUND GENERATOR WITH FIELD COILS OPPOSING			
Load Resistors (number)	Output Voltage (V)	Output Current (A)	Output Power (W)
0			
1			
2			
3			
4			
5			

DATA TABLE 2. ALTERNATOR.

OUTPUT VOLTAGE VERSUS FIELD CURRENT					
Field Current (mA)					
Output Voltage (V)					

ALTERNATOR OUTPUT			
Load Resistors (number)	Output Voltage (V)	Output Current (A)	Output Power (W)
0			
1			
2			
3			
4			
5			

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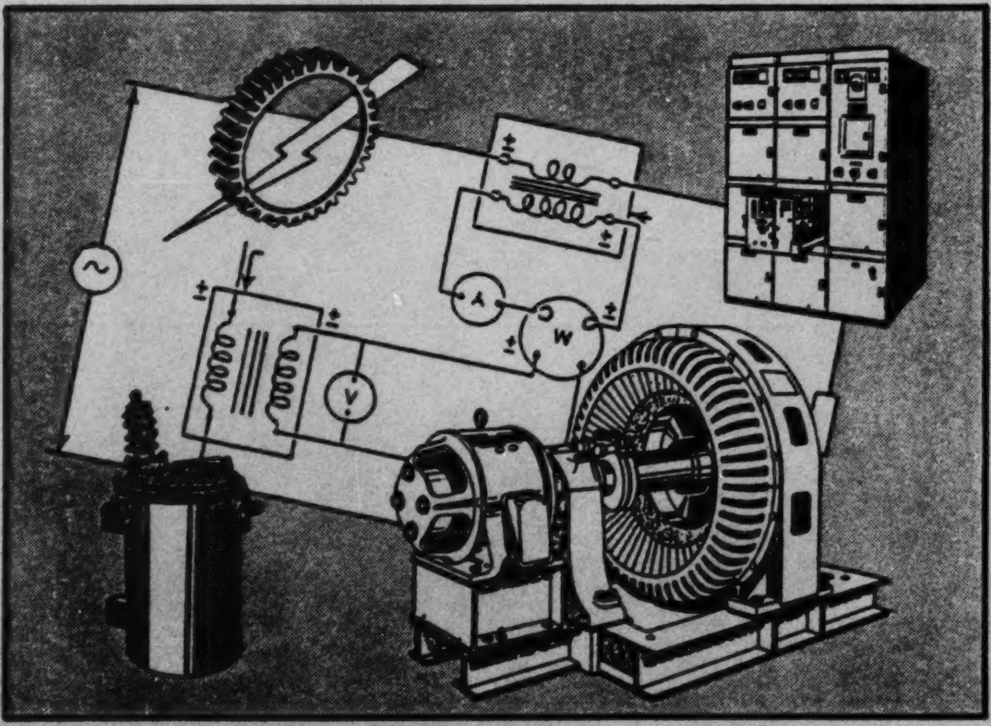
ENERGY TECHNOLOGY
CONSERVATION AND USE

ELECTROMECHANICAL DEVICES



MODULE EM-05

D. C. MOTORS AND CONTROLS

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

A direct current electric motor is an electromechanical device that converts d.c. electrical energy to rotational mechanical energy. These motors are available in sizes ranging from small instrument motors powered by batteries to large models producing several hundred horsepower. All d.c. motors have similar design features. Their output characteristics depend upon the connections of their field coils. Shunt motors have field coils connected in parallel with the armature and produce almost constant speed with a varying load. Shunt motors designed for speed control can be operated over a wide range of speeds. Series motors have field coils connected in series with the armature. Their speed varies with load, and they produce large starting torques. Compound motors contain both shunt and series coils and have operating characteristics that are a compromise between the shunt motor and the series motor.

This module discusses basic d.c. motor principles, construction and operation of the three types of d.c. motors, control circuits for d.c. motors, and common problems encountered with d.c. motors. In the laboratory, the student will construct a motor control circuit and measure the output characteristics of a shunt motor.

PREREQUISITES

The student should have completed Module EM-04 of "Electromechanical Devices."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Draw and label a diagram of a simple d.c. motor.
2. Explain the purpose, location, and electrical connection of a magnetic interpole in a d.c. motor.
3. Draw schematic diagrams showing the electrical connections of the following types of d.c. motors:

   a. Shunt
   b. Series
   c. Compound
4. Draw and label diagrams showing rotational rate and output torque as functions of motor current for each of the three types of d.c. motors.
5. Explain the origin of the counter electromotive force in a shunt motor and explain how the CEMF limits armature current and motor speed in the shunt motor.
6. Explain the conditions that can lead to motor damage due to excessive speed in each of the three types of d.c. motors.
7. Describe the characteristics of the mechanical loads typically driven by each of the three types of d.c. motors.
8. Draw and label diagrams of three-terminal and four-terminal manual starter circuits for d.c. motors. Explain the operation of each type.
9. Given schematic diagrams of a CEMF starter and a series locked-out starter, explain the operation of each.
10. Draw and label diagrams showing the following methods of speed control for shunt motors. Explain the operation of each method.
    a. Field rheostat
    b. Armature rheostat
    c. Ward-Leonard system
11. Explain two methods that can be used for motor braking.
12. Explain, with the use of an efficiency versus current curve, why electric motors must be operated near their rated load for maximum efficiency.
13. List the three categories of motor failure.
14. Given the appropriate equipment, construct a d.c. motor control circuit, make the necessary measurements, and plot the characteristic curves of a shunt motor.

THE SIMPLE D.C. MOTOR

Figure 1 shows the basic components of a simple d.c. motor. This motor consists of a fixed magnetic field and a loop of wire connected to a d.c. voltage source through a commutator. The commutator consists of two conductive segments (A and B), which are each connected to one side of the wire loop (C and D). A brush connects each commutator segment to the voltage source. This is the same basic construction as that of a d.c. generator. In the generator, mechanical input energy is converted to electrical output energy. In the motor, the process is reversed, converting electrical input energy to mechanical output energy.

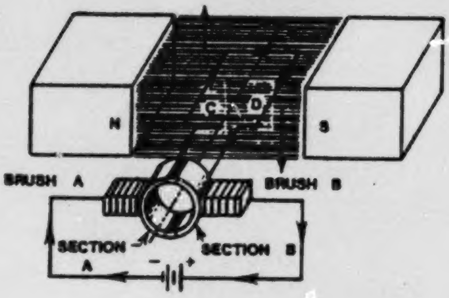


Figure 1. Construction of a Simple d.c. Motor.

In Figure 1, current flow through coil segment C produces an upward force on that segment. Current flow in the opposite direction in segment D produces an equal downward force. These forces provide the torque to rotate the armature coil around its axis as shown. This same coil position is shown in Figure 2a. In Figure 2b, the armature has rotated through one quarter of a turn, and "commutation" is occurring; that is, each half of the split ring is moving to contact the other brush. Just before commutation, the force on coil segment C is still upward, and the force on segment D is downward. This produces no torque on the armature, but the armature's angular momentum causes it to continue to turn. Immediately following commutation, the current in the coil and the direction of force on the wire segments have reversed. The armature continues to rotate to the position shown in Figure 2c with increasing torque. Figures 2a and 2c are the positions of greatest torque because the

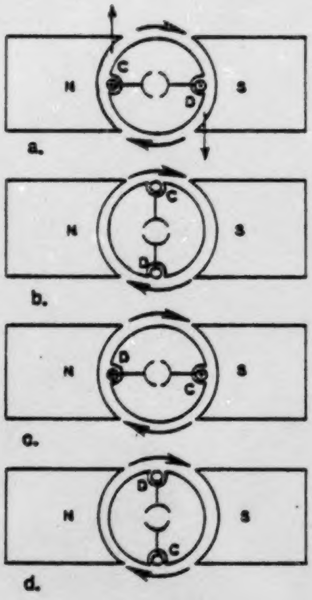


Figure 2. Rotation of Simple d.c. Motor.

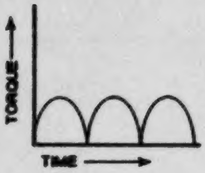


Figure 3. Output Torque of a Simple d.c. Motor.

applied forces act with the greatest lever arms. In Figure 2d, commutation occurs again. The pulsating output torque of this simple d.c. motor is shown as a function of time in Figure 3.

The torque of a d.c. motor can be made almost constant by using additional armature coils, as shown in Figure 4. These coils are connected in series, as shown in Figure 5, to provide current flow through all coils in the direction indicated in Figure 4. Thus, while the vertical coil in Figure 4 is undergoing commutation, the other coil continues to produce torque.

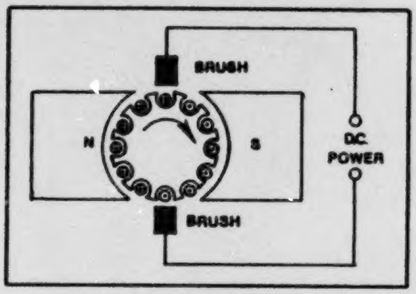


Figure 4. Armature Coils in Slots Around Armature Core.

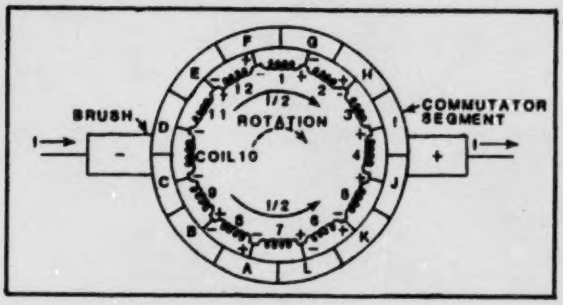


Figure 5. Armature Winding for Two-Pole Motor.

The fixed magnetic field of d.c. motors is provided by field coils with a d.c. current flow. These coils are wound on a stator frame similar to that of a d.c. generator. Many motors are designed with multiple poles in the stator field. Figure 6 shows the field windings, brushes, and coil segments of a four-pole d.c. motor. This arrangement provides greater output torque with the same armature current because each wire segment moves in a direction perpendicular to the field direction more frequently. The armature coil connections are arranged to provide coil current in the direction shown, and one pair of brushes is provided for each pair of field poles.

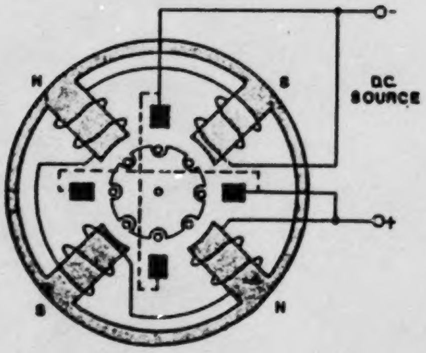


Figure 6. Four-Pole Shunt Motor.

CONSTRUCTION OF D.C. MOTORS

The armature core of a d.c. motor is of laminated construction just as that of a d.c. generator because, as in the generator, the direction of armature magnetic field reverses when the coil current reverses. Armature coils consist of only a few turns (usually only one) to reduce coil inductance. This reduces the reverse EMF of the coil during commutation and, thus, reduces sparking of the commutator.

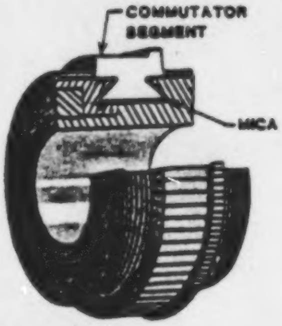


Figure 7. Cutaway View of a d.c. Motor Commutator.

The construction of the commutator is shown in Figure 7. Each commutator segment is a solid piece of copper. The segments are insulated from the mounting ring and from each other by layers of mica. Each commutator segment has a slot in which the coil ends rest. Coil ends are soldered or brazed in place.

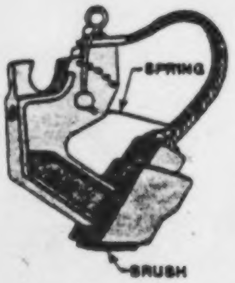


Figure 8. Brush and Holder for a d.c. Motor.

The brush and brush holder of a d.c. motor are shown in Figure 8. The brush is made of carbon and is free to slide in the brush holder. A spring presses the brush against the commutator with the correct pressure.

The stator frame of a d.c. motor can be of laminated construction, but often it is not because the constant magnetic fields in the stator core do not produce eddy currents. The windings are similar to those of d.c. generators discussed in Module EM-04, "Generators and Alternators."

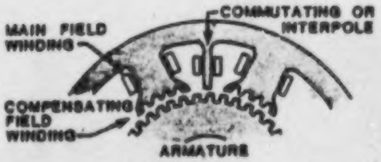


Figure 9. Section of a d.c. Machine Showing Compensating Field.

Commutator sparking is reduced in many d.c. motors by the addition of magnetic interpoles in the stator. The interpole is a narrow magnetic pole positioned so that a coil segment undergoes commutation while it is directly under the interpole. This is shown in Figure 9. The effect of the interpole is to greatly reduce the magnetic field strength during commutation. Figure 10 shows a four-pole stator with two interpoles. Figure 11 shows the electrical connections of interpoles, also called "commutating poles," in a d.c. motor with four main poles and four interpoles. The interpoles are connected in series with the armature so their field strength will be proportional to armature current.

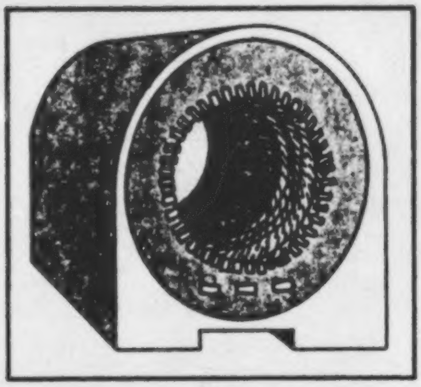


Figure 10. Stator Frame, Field Poles, and Field Windings of d.c. Motor.

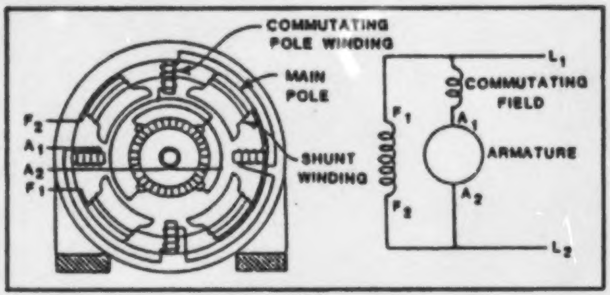

COMMUTATING POLE WINDING
MAIN POLE
SHUNT WINDING
F_2
A_1
A_2
F_1
L_1
COMMUTATING FIELD
F_1
A_1
ARMATURE
F_2
A_2
L_2

Figure 11. Wiring Diagrams of a Shunt-Wound d.c. Motor with Interpoles.

TYPES OF D.C. MOTORS

A d.c. motor is classified according to the connection of its main field coils. (Interpole coils connected in series with the armature can be present in any type.) The three types are shown schematically in Figure 12.

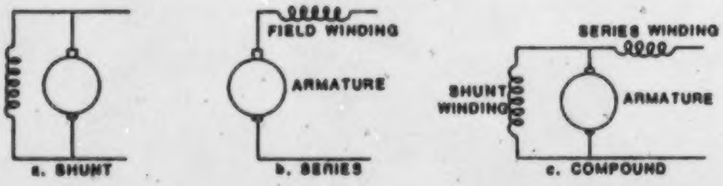

FIELD WINDING
ARMATURE
SERIES WINDING
SHUNT WINDING
ARMATURE
a. SHUNT
b. SERIES
c. COMPOUND

Figure 12. Three d.c. Machine Connections.

In the shunt motor (Figure 12a), the armature and the field coils are connected in parallel. The field coils are made of many turns of small wire. Current through the field coils is limited by the wire resistance and is constant at constant applied voltage. Thus, the stationary magnetic field of a shunt motor is constant with a constant applied voltage. Increasing the applied voltage increases the field strength and the output torque of the motor.

The resistance of the armature coils is so low that extremely high currents will flow through the armature if it is connected directly to its rated voltage while the motor is stopped. Methods of limiting armature current during motor starting are discussed later in this module. When the motor is running, armature current is limited by the counter electromotive force (CEMF) of the armature coil.

Recall from Module EM-04, "Generators and Alternators," that a voltage is induced whenever a coil moves through a magnetic field. This same process results in the generation of a voltage in the moving coil in a d.c. motor. The direction of the induced voltage is opposite the direction of the voltage applied to the coil by the external source — thus, the name "counter electromotive force." The magnitude of the CEMF depends upon the rotational rate of the armature. Increasing motor speed results in an increased CEMF. The armature current depends on the difference in the applied voltage and the CEMF.

A shunt motor with no mechanical load runs at a constant speed at which the CEMF is slightly less than the applied voltage. The small armature current produces a torque that balances the frictional torque of the motor. If the mechanical load on the motor is increased, the armature slows down slightly. This reduces the CEMF and, thus, increases armature current. The increased current produces greater output torque to maintain motor speed.

The characteristic curves of a shunt motor are shown in Figure 13. The motor current is actually determined by the motor load and increases as load increases, but characteristic curves are typically drawn as a function of current rather than load. In the shunt motor, there is a slight drop in speed as load and current increase. The full-load speed is typically 5 to 15% less than the no-load speed. Thus, shunt motors run at nearly constant speed for any load below the rated capacity and do not slow very much even when greatly overloaded.

The speed of a shunt motor can be controlled by controlling either the field current or the armature current by techniques discussed in a later section of this module. Shunt motors without speed controls are used to drive machinery designed to operate at a constant speed with variable load and relatively low starting torque.

If the shunt coil of a motor is disconnected from the voltage source while the motor is in operation with the armature connected, the strength of

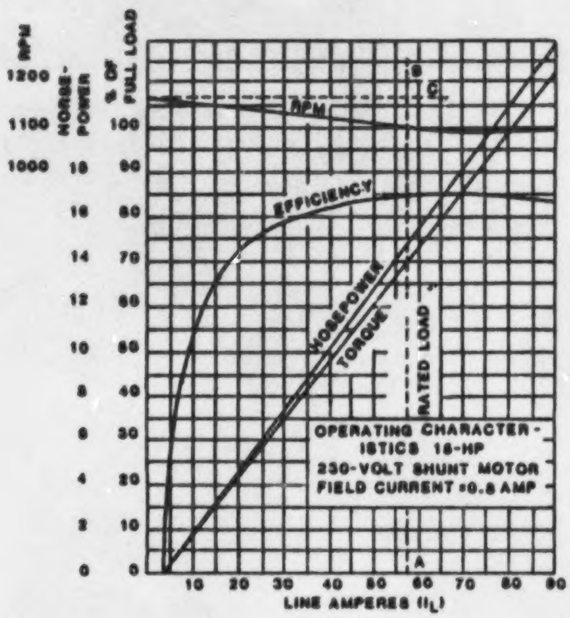


Figure 13. Operating Characteristic Curves of a Typical 15-hp, 230-volt, Shunt-Wound d.c. Motor.

the stationary magnetic field decreases to the residual field of the stator core. This greatly reduces the armature CEMF and proportionately increases armature current. The motor speed will increase because of the torque produced by the large current flow through the residual field; but the armature may be destroyed by overheating due to excessive current. If the motor is initially operating with no load or a light load, its speed will increase until the commutator and windings fly apart. Circuit breakers are often included in the armature circuits of shunt motors to open the circuit in case of field coil failure.

In the series motor (Figure 12b), the armature and field coils are connected in series. The field coils consist of a few turns of large wire since they must carry the large armature current. The shunt motor will run at a constant speed with a constant load with its current limited by the CEMF of its armature. As load increases, speed decreases. This reduces the CEMF, allowing more current to flow through both the field coils and armature coils. The higher field current produces a stronger field, and the motor stabilizes at a lower speed with higher torque and higher current.

The characteristics of a series motor are shown in Figure 14. The torque of the series motor increases as the square of the current. This allows much greater starting torques than those of shunt motors. For this reason, series motors are often used in cranes and for traction work where large starting torques are required.

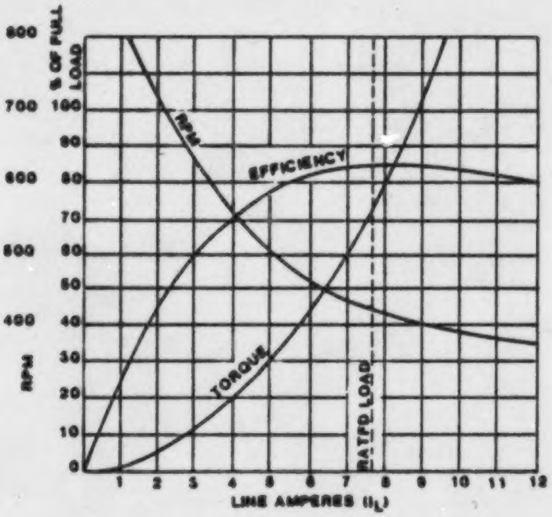


Figure 14. Operating Characteristic Curves of a Series d.c. Motor.

If the load of a series motor is reduced, the motor speed increases, and the motor current decreases, as shown in Figure 14. If the load is removed entirely, the speed will increase until the motor is destroyed. For this reason, a series motor must never be connected to an electrical power source unless it is also connected to a mechanical load. Series motors should never be connected to a mechanical load by a belt drive. If the belt breaks, the motor will "run away." In a series motor, current decreases as rotational rate increases. Thus, limiting motor current will not limit motor speed. The speed of a series motor varies greatly with load and cannot be regulated, although motor speed with a constant mechanical load can be changed by changing the applied voltage.

The compound motor (Figure 12c) has both shunt and series coils in its stator. Thus, its characteristics lie between those of the shunt motor and the series motor, as shown in Figure 15. The speed of the compound motor changes as load changes, but the change is less than for the series motor. The low speed (high current) torque of the compound motor is greater than that of the shunt motor but less than that of the series motor. With no load, a typical compound motor runs at a speed of about 20% greater than its loaded speed. Compound motors are available with a variety of characteristic curves, depending upon the relative field strength provided by the series coils and the shunt coils.

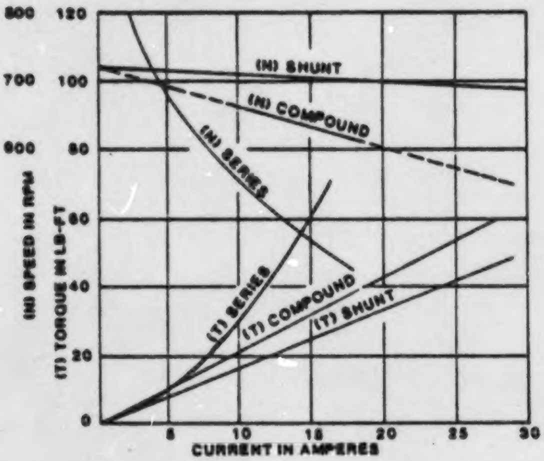


Figure 15. Speed-Torque Characteristic Curves for Compound, Shunt, and Series d.c. Motors of Equal Size.

Compound motors are used for loads requiring high starting torques or for loads subject to large torque variations. Applications include elevators, air compressors, printing presses, and conveying machinery. The speed of compound motors cannot be regulated as can that of a shunt motor, but the speed at a constant load can be varied by varying the shunt field. The compound motor will not "run away" if its load is removed, but it will behave similar to a shunt motor if its shunt coil is disconnected during motor operation.

D.C. MOTOR CONTROLS

Small d.c. motors can be designed for "across the line" starting in which the motor is started by connecting it directly to a voltage source at the motor voltage rating. Motors larger than 5 hp and many smaller models require starting resistors in series with the armature to limit armature current to a safe level during starting.

Figure 16 shows the starting circuit of a shunt motor. The main switch is closed, with switches 1, 2, and 3 opened. The total resistance (R_1 + R_2 + R_3 + armature resistance) limits the armature current to about 200% of the rated maximum current. This momentary high current provides additional starting torque but does not flow long enough to produce a large temperature increase. The shunt field coils are connected directly to the power source. Thus, shunt field strength is not affected by the starting resistors.

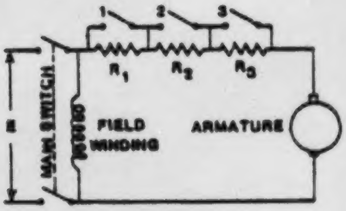


Figure 16. Motor-Starting Circuit.

Figure 17 shows motor speed and armature current during starting with the circuit in Figure 16. Armature current decreases as speed decreases. When armature current has fallen to 100% of the rated value, switch 1 is closed, shorting R_1. This increases armature current again to 200% maximum, and motor speed increases. This process is continued until all the series resistance has been removed and the motor is running at its rated speed. The number of resistors in motor starter circuits varies from two to a dozen, depending on the characteristics of the motor to be started.

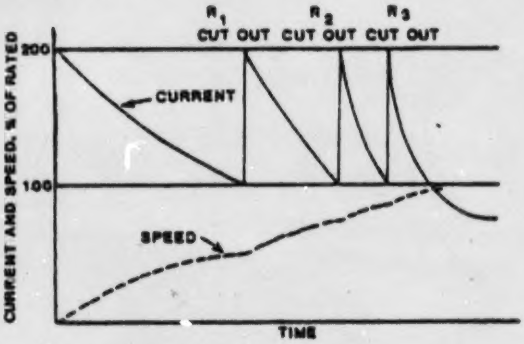


Figure 17. Current and Speed Versus Time During Starting Operation.

When a similar starter circuit is used with a series motor or a compound motor, the series field coil current is also increased to a maximum of 200% of the rated value. This doubles the series field strength and accounts for the greater starting torque of the series motor.

Figure 18 shows a manual three-terminal motor starter. The operating handle is moved forward by hand to remove the series resistors. With all the resistors removed, the handle is held in place by a holding coil connected in series with the shunt field. If the shunt field current is interrupted

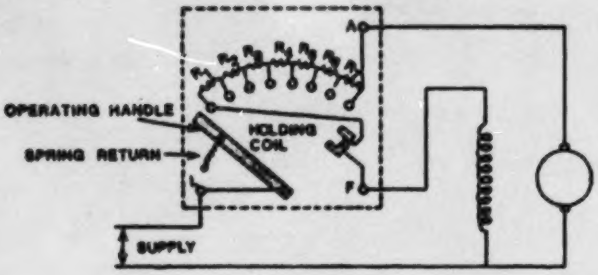


Figure 18. Connection of Three-Terminal Manual Starter.

for any reason, this coil is de-energized, and a spring returns the operating handle to the original position and interrupts armature current. This protects the shunt motor from run-away due to reduced field current.

If the speed of a shunt motor is controlled by controlling the shunt field current, the holding coil current may be reduced to a value that will not hold the operating handle. In this case, the four-terminal starter shown in Figure 19 can be used. The folding coil is this starter is wired in series with the armature. This assures the holding power of the coil but does not provide any protection from armature current or speed increase if the field coil fails.

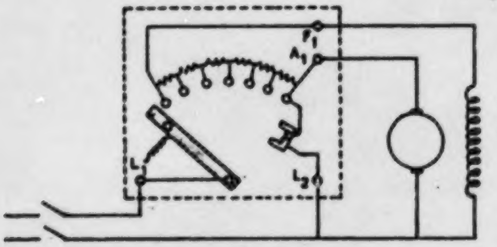


Figure 19. Connection of Four-Terminal Manual Starter.

In automatic motor starters, the resistors in series with the armature are removed automatically. In definite-time automatic starters, time delay relays are used to short circuit the resistors after a definite time. Such starters must be carefully matched to both the motor and the load for proper performance. When d.c. motors are to be started automatically under varying load conditions, current-limit automatic starters are used. These starter circuits change series resistance in response to armature current rather than at a fixed rate.

Figure 20 shows a CEMF motor starter circuit. Pressing the start button energizes coil M and closes all contacts labeled "M" in the diagram. This connects the applied voltage to the field windings and to the series circuit composed of the armature and R_1 and R_2. Coil 1 is connected in parallel with the armature. Initially, most of the voltage drop is across R_1 and R_2, and the armature voltage drop is too low to energize coil 1. As motor speed increases, the armature CEMF increases to produce an armature voltage sufficient to energize coil 1, closing the contacts labeled "1" in the diagram and shorting R_1.

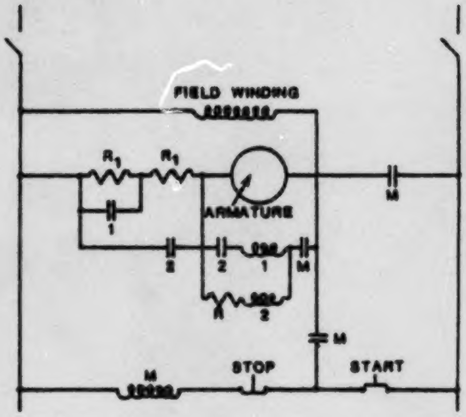


Figure 20. Connection of CEMF Starter.

Coil 2 is identical to coil 1 and is also connected across the armature. Resistor R in series with coil 2 reduces current through this coil. This means that a greater armature voltage is required to energize coil 2 than that required for coil 1. When the motor CEMF reaches this value, coil 2 is energized, shorting both R_1 and R_2. The normally closed contacts labeled "2" also open to remove coil 1 from the circuit and protect it from over-current conditions. This starter circuit shows only two resistors and coils for simplicity, but practical starters may contain several additional coils and resistors.

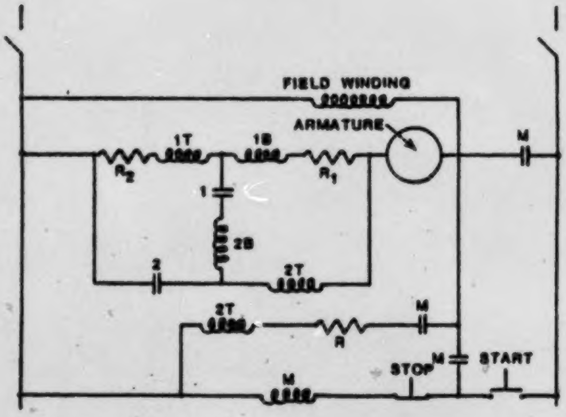
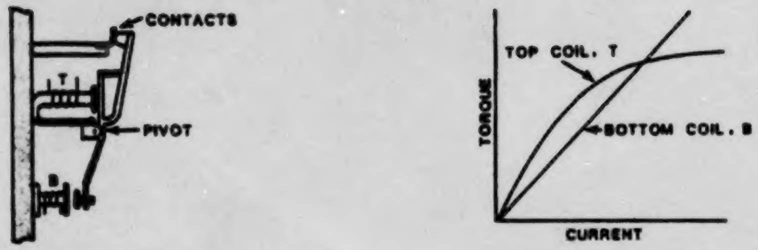


Figure 21. Series Locked-Out Starter Details.

Figure 21 is a schematic for a series locked-out d.c. motor starter. The relays used in this circuit are shown in Figure 22a. Each contains two coils. The top coil T acts to close the relay contacts. Its core contains little iron and is easily saturated by d.c. current flow through the coil. The bottom coil B acts to open the relay contacts. Its coil contains considerably more iron and does not saturate at normal operating currents. The torque versus current curves of the two coils are shown in Figure 22b.

In the starter circuit, the two coils are connected in series and carry the same current. At low current values, the top coil holds the relay contacts closed. If current exceeds a predetermined value, the torque of coil B exceeds that of coil T, and the contacts are opened.



a. SERIES LOCKED-OUT CONTACTOR (IN CLOSED POSITION)

b. TORQUE VS. CURRENT CURVES

Figure 22. Series Locked-Out Contactor.

When the start button in Figure 21 is pressed, coil M is energized, and all contacts labeled "M" close. The armature current flows through resistors R_1 and R_2 and through coils 1T and 1B, which are located together on one relay. Since the initial current exceeds the maximum running current, coil 1B holds contact 1 open. When the current has dropped to the maximum rated current, coil 1T closes contact 1. This connects the series combination of coil 2B and 2T in parallel with 1B and R_1. Since the resistance of R_1 greatly exceeds that of 2B and 2T, most of the current flows through the coils of relay 2. This current also flows through coil 1T of relay 1 to maintain it in the closed position. At this point, armature current is limited by R_2 to a value of 200% of the rated current. Thus, coil 2B holds contact 2 open. When the current once again drops to the rated value, the torque produced by coil 2T exceeds that of 2B, and contact 2 closes. This removes resistor R_2 and coil 2B from the circuit. The armature current continues to flow through coil 2T to keep contact 2 closed. Coil 2T' is an auxiliary coil included in relay 2 to maintain it in the closed position at low armature currents.

Once a shunt motor has been brought into operation with all series starting resistors removed from its armature circuit, its speed can be controlled by controlling either its armature voltage or field current. Figure 23a shows a variable resistor in series with the armature of a shunt motor. Increasing the resistance of this series resistor increases its voltage drop and decreases the voltage drop across the armature. This results in lower motor speed. This technique is seldom used because large amounts of power must be dissipated by the series armature rheostat. Starting resistors should never be left in the circuit for this purpose because they are rated for intermittent operation only and will soon be destroyed if placed in continuous operation.

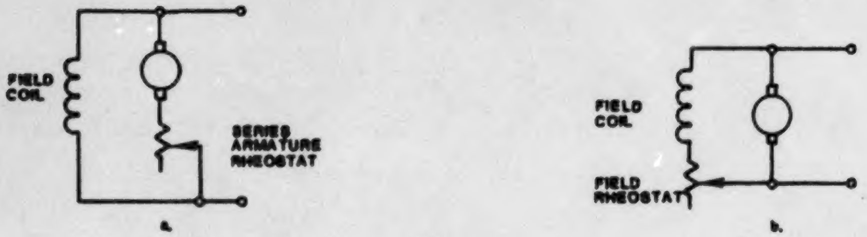


Figure 23. Speed Control Circuits for Shunt Motors.

Figure 23b shows a shunt motor in which the speed is controlled by a rheostat in the field circuit. Increasing the resistance reduces field current. This reduces armature CEMF and results in higher armature current and increased motor speed. The rheostat carries only the small field current and does not consume high power. This technique is commonly used for speed control on shunt motors to vary the speed by as much as a factor of four.

Figure 24 shows the Ward-Leonard system of speed control often used in large d.c. motors requiring operation over a wide range of speeds. The shunt field coil is energized by a constant d.c. voltage applied from the power source. The armature current is supplied by a d.c. generator that is powered by a separate constant-speed motor. The field coils of the generator are energized by the same voltage source that provides the d.c. motor field current. A variable resistor is used to control the generator field current. When the generator field current is zero, no voltage is induced in the generator rotor. Thus, no current is supplied to the d.c. motor armature and no torque is produced. Increasing the generator field strength increases the motor armature current and motor speed.

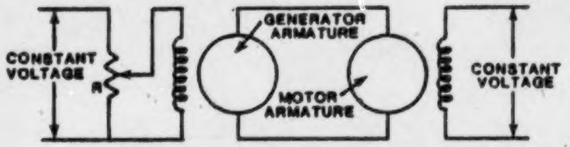


Figure 24. Ward-Leonard System of Speed Control.

The speed of a compound motor cannot be set at a fixed value as in the shunt motor, but a rheostat in series with the shunt coil can be used to adjust its speed at a constant load. This is not a common practice since compound motors are usually employed with variable loads. The speed of a series motor can be changed by the use of a variable resistor in series with both the armature and field coils; but this is rare except in the case of hand-held power tools.

The direction of rotation of a d.c. motor can be reversed by reversing the connections of either the field coils or the armature. Reversing both connections will not change the direction of rotation. In the Ward-Leonard system, motor armature current is reversed by reversing the field current in the generator.

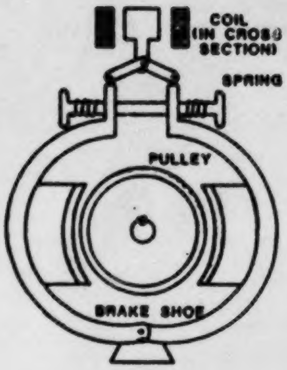


Figure 25.
Friction Brake.

An electric motor can be stopped by disconnecting its power source and allowing the motor to coast to a stop. If more rapid stopping is required, braking can be provided by two means. Figure 25 shows a friction brake used to stop a motor. A solenoid presses the brake shoes against a pulley to provide friction. Figure 26 illustrates dynamic braking in a shunt motor. The shunt field remains energized. The armature is disconnected from the power source and connected to a resistive load. The rotating armature generates a voltage that produces a current through the resistor. The motor functions as a loaded generator with no mechanical input power and rapidly comes to a stop.

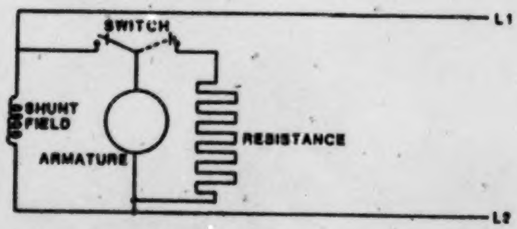


Figure 26. Connections of a Dynamic Brake to a d.c. Motor.

MOTOR EFFICIENCY

Figures 13 and 14 include curves showing motor efficiency for shunt and series motors as functions of motor current. In both cases, the maximum efficiency occurs at the rated motor load. Thus, maximum efficiency in the conversion of electrical energy to mechanical energy is achieved when an electric motor is operated near its rated load. Exceeding the rated load for a long period of time will cause the temperature of the motor to increase to dangerous levels. Operating a motor at a fraction of its rated load is inefficient.

The maximum efficiency of a d.c. motor varies from about 75 to 93%, depending on motor size and design. Shunt field losses are due to the electrical resistance of the shunt coils. Armature circuit losses are due to resistance of the armature coils, brush contacts, and series field coils. No-load rotational losses include hysteresis and eddy currents in the armature core and air and bearing friction. Stray load losses are difficult to determine exactly but include uneven distribution of current among parallel windings and distortions in the magnetic fields.

MOTOR MAINTENANCE AND TROUBLESHOOTING

Volumes can be written on motor maintenance and troubleshooting, and many have been. This section discusses briefly some of the more common problems encountered and ways they can be prevented or corrected. Failures in d.c. electric motors can be grouped into three broad categories:

- Bearing failures
- Commutator failures
- Open or shorted coils

Bearing failure occurs because of improper lubrication or because of excessive loading of the bearings. Routine maintenance of electric motors should include a regular schedule of bearing lubrication. Misalignment of external shafts connected to the motor shaft is the major cause of bearing wear. Motor bearings should have a running temperature of no more than 40°C above the temperature of the surrounding air. A bearing that is too hot to touch is well on its way to failure and should be inspected immediately.

Commutator and brush failures can result from a variety of causes. They are usually evidenced by excessive brush sparking, streaking or burning of the commutator, or brush "chatter." Some of the more common commutator faults and their causes are listed below.

- Brushes that fit too loosely in their holders tend to vibrate or chatter. This results in sparking and excessive brush temperatures.
- A broken brush tension spring or dirt between the brush and brush holder may result in poor contact between the brush and commutator.

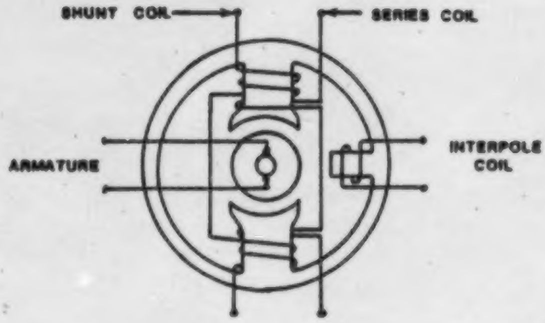
- A buildup of oil or other films on the commutator increases the electrical resistance between the commutator and brushes. Eventually an arc will burn a hole in this film. This produces uneven current distribution across the brush and leads to "streaking" around the commutator.
- Some soft brushes cause excessive commutator wear due to "copper picking." Small amounts of copper are deposited on the brush surface. The lowered contact resistance at these points results in uneven current distribution that can cause severe, uneven commutator wear.
- When a motor is not operated for long periods of time, mild acid formed from moisture and contaminating gases in the air can set up battery action between the carbon brushes and the metallic commutator. This etches a "footprint" of the brush into the commutator surface.
- Most d.c. motors are designed so the brush location can be rotated circumferentially for the best operation. If the brushes are shifted from the optimum position, sparking and poor performance may result.

For proper performance, the commutator and brushes should be kept clean and free of oil or other films. Worn brushes should be replaced only with exact replacements and should be aligned with care.

Open circuits in the field or armature coils can occur because of mechanical failure or conductor melting due to excessive currents. Such faults can be located easily with an ohmmeter. The shorting of field windings because of insulation failure is a much more common problem. The leading cause of insulation failure is moisture in the field coils. Moisture can enter the coils from external fluid leaks, mists, and splashes. If motors are idle for long periods in high humidity, moisture will condense in the field coils. Motors and generators should never be operated when damp.

The condition of the field coil insulation can be checked by measuring the electrical resistance between the field coils and the stator frame. If the resistance is less than one megohm, the motor should be dried before operation. This can be accomplished by removing the rotor and drying the field coils with heating lamps or by passing a small current through the coils.

EXERCISES



1. The diagram at the right shows the electrical terminals of a compound motor with one interpole. Draw the electrical connections of this motor.
2. Explain what happens if the mechanical linkage between a series motor and its load fails while the motor is in operation.
3. Explain what happens if the field coil of a shunt motor fails during motor operation.
4. Explain the difference in three-pole and four-pole manual motor starters and the advantage of each.
5. Motor circuits require switching of large currents. This can be accomplished with an air circuit breaker or a magnetic blow-out circuit breaker. Locate descriptions of the operation of these devices in the library and write a brief description of each.
6. Disassemble a d.c. electric motor and sketch the parts.
7. Write a brief description of how CEMF limits the speed of a shunt motor.

LABORATORY MATERIALS

d.c. shunt motor, 115 V d.c., 1 hp, 1200 rpm, with pulley
d.c. milliammeter, 0-250 mA
d.c. ammeter, 0-20 A
d.c. voltmeter, 0-150 V
Four SPST switches, 115 V d.c., 20 A
DPST switch, 115 V d.c., 20 A
4Ω, 50-W resistor
2Ω, 20-W resistor
1Ω, 10-W resistor
0.5Ω, 5-W resistor

500Ω, 100-W rheostat
d.c. power supply, 115 V d.c., 20 A
Prony brake
Scale, 0-5 lb
Water cooling for prony brake
Splash shield for motor
Tachometer
Connecting wires

LABORATORY PROCEDURES

1. Fill in the motor specifications in the Data Table.
2. Construct the circuit shown in Figure 27. Do not connect prony brake to motor.

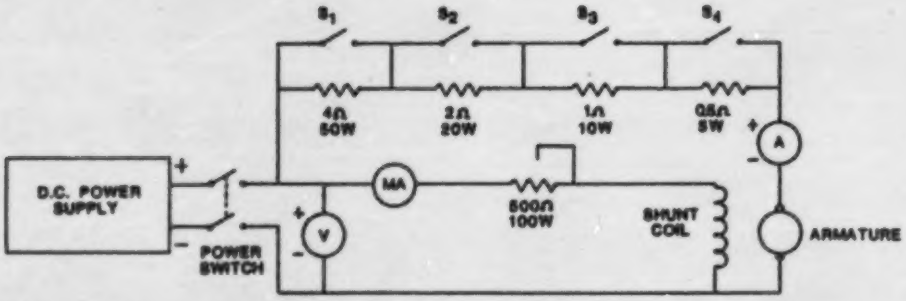


Figure 27. Experimental Motor Circuit.

3. Set the field rheostat for minimum resistance. Open switches S_1, S_2, S_3, and S_4.
4. With power switch open, turn on the d.c. power supply.
5. Close power switch momentarily and observe direction of motor rotation. If motor rotation is not in the proper direction for use of the prony brake, reverse the connections of the shunt coil and check again.
5. Start the motor, using the following procedure:
   a. Close the power switch while watching the ammeter. The current will assume a high value momentarily and drop off.
   b. When the current drops to about 7.5 A, close S_1. The current will rise again.

c. Close S_2, S_3, and S_4 in succession each time current drops to 7.5 A. NOTE: With the motor unloaded, the speed will increase rapidly and the current will drop rapidly.

7. When the motor reaches constant speed with all switches closed, measure and record rotational rate, field current, armature current, and applied voltage in Trial 1 of the Data Table.
8. Turn off the power switch and open S_1-S_4.
9. Attach the prony brake, as shown in Figure 28. Tighten the wing nuts enough to hold the prony brake in place as the motor rotates but not enough to produce significant friction. Be sure the splash shields and water supply are in place.

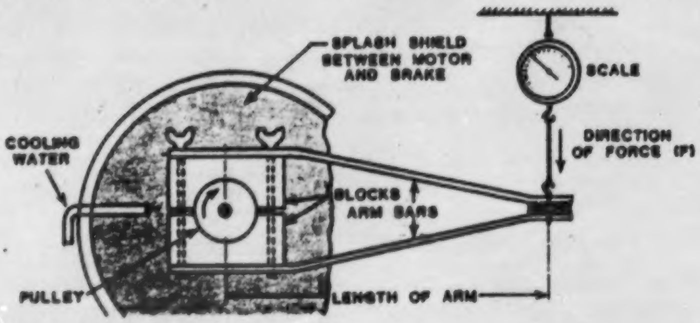


Figure 28. Prony Brake.

10. Turn on motor, using procedure from Step 5.
11. Turn on prony brake cooling water. Verify cooling of the brake and splash protection of the motor.
12. Calculate the force indicated on the scale when the motor is at full load by dividing rated torque by lever arm.
13. Tighten the wing nuts to produce one-tenth the value calculated in Step 12. Record voltage, armature current, rotational rate, and force in the Data Table.
14. Increase the tension of the prony brake in steps of one-tenth of rated force until a maximum of 120% of the rated force is reached, recording data after each increase.
15. Reduce motor load to 75% of rated value and turn off the power switch.
16. Open switches S_1-S_4.

17. Start the motor under load, following the previous procedure. Note differences in starting with a load and in starting with no load in the section of the Data Table headed "Motor Starting."
18. Reduce the prony brake tension to the minimum.
19. Set the field control rheostat to produce a rotational rate of one and a half times the rated value. Record the field coil current in Trial 2 of the Data Table.
20. Repeat Steps 13 and 14 for this rotational rate.
21. Turn off the motor and cooling water. Remove the prony brake from the motor, and set the rheostat for minimum resistance.
22. Restart the motor. Change the motor speed by adjusting the field rheostat. Record the field current and rotational rates in the Data Table. Do not exceed 200% of the rated motor speed.
23. Turn off the motor and power supply.
24. Complete the Data Table.

    1 rpm = $\pi/30$ rad/sec

    550 ft·lb/sec = 1 hp = 746 W

    Total current = field current + armature current
25. Plot the following graphs on three sheets of graph paper:
    a. Torque, speed (rpm), and efficiency versus total current for Trial 1
    b. Torque, speed, and efficiency versus total current for Trial 2
    c. Speed versus field current

Portions of this laboratory procedure can be modified to determine the output characteristics of series motors and compound motors. Recall that series motors must never be operated with no load.

DATA TABLE.

Motor Specifications:

Voltage ______ V

Power ______ hp

rpm ______

Current ______ A

Torque ______

TRIAL 1:

Field coil current ______

Full load force ______

Voltage	Armature Current	Total Current	Input Power	Rotational Rate		Lever Arm	Force	Output Power		Efficiency
V	A	A	W	rpm	rad/sec	ft	lb	$\frac{ft \cdot lb}{sec}$	W	%

Motor Starting:

Data Table. Continued.

TRIAL 2:

Field coil current _____

Voltage	Armature Current	Total Current	Input Power	Rotational Rate		Lever Arm	Force	Output Power		Efficiency
V	A	A	W	rpm	rad/sec	ft	lb	$\frac{\text{ft}\cdot\text{lb}}{\text{sec}}$	W	%

MOTOR SPEED CONTROL (No Load):

Field Current (mA)	Rotational Rate (rpm)

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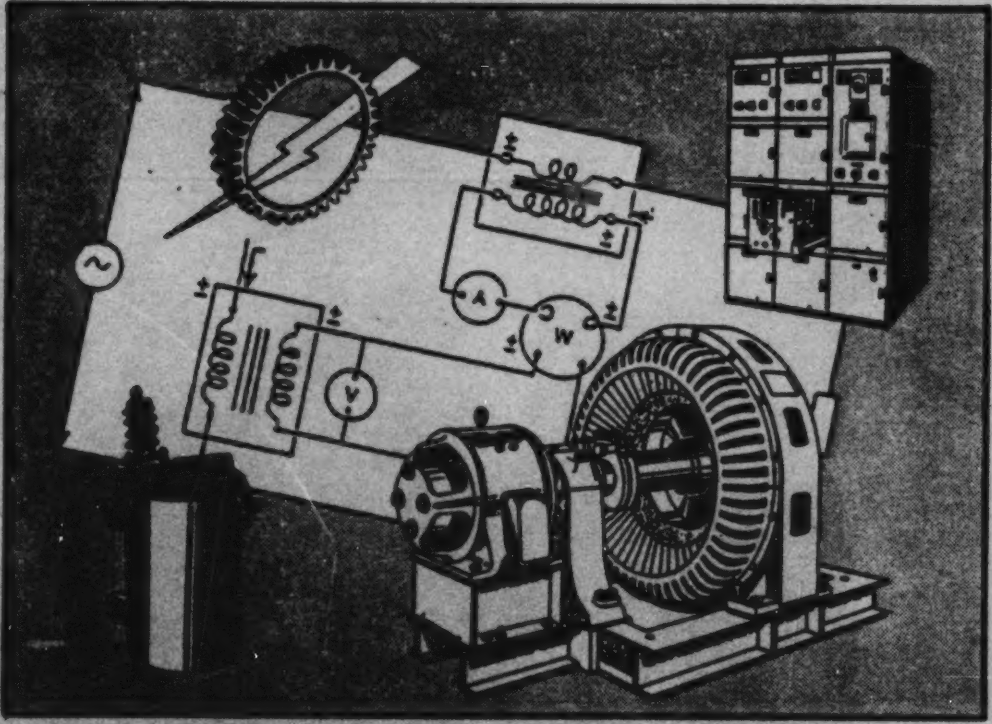
ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTROMECHANICAL DEVICES



MODULE EM-06

A. C. MOTORS AND CONTROLS

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

An a.c. electric motor is an electromechanical device that converts alternating current electrical energy into rotational mechanical energy. This motor ranges in size from a clock motor with powers of 0.003 horsepower to an industrial motor of 1000 hp or more. An a.c. motor can be conveniently classified in the following three categories:

- Synchronous motor – rotates at a rate that is an integral fraction of the applied a.c. frequency. The rotor has permanent magnetic poles that lock in step with the rotating field of the stator.
- Induction motor – rotates at slightly less than synchronous speed. The magnetic field of the rotor is produced by currents induced in the rotor coils by the changing stator field.
- Universal motor – similar to a d.c. series motor in construction and operation.

This module discusses the construction, operation, control, and application of a.c. motors. In the laboratory, the student will operate three types of a.c. motors.

PREREQUISITES

The student should have completed Module EM-05 of "Electromechanical Devices."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Explain what changes occur in the stator magnetic field of a six-pole, three-phase a.c. motor during three complete cycles of the applied a.c. current.
2. Explain the difference in the origin of the rotor magnetic field in a synchronous motor and an induction motor.
3. Given the frequency of the a.c. current of an induction motor and any three of the following quantities, calculate the fourth:

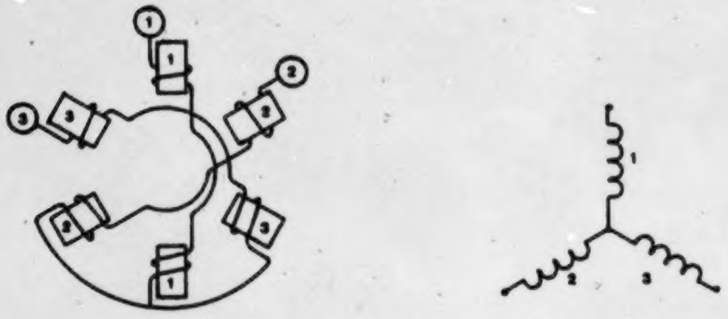
   - a. Number of magnetic poles in the rotor
   - b. Synchronous speed
   - c. Operating speed
   - d. Slip speed in percent of synchronous speed

4. Explain the difference in the power factor of a synchronous motor and an induction motor.
5. Explain, with the use of diagrams, the difference in a salient-pole rotor and a nonsalient-pole rotor in a synchronous motor.
6. Explain the purpose of damping coils in a synchronous motor.
7. Explain two methods of starting synchronous motors. Include when the rotor field should be energized.
8. Draw curves showing torque versus motor speed for three induction motors with three different values of rotor resistance.
9. Explain the differences in characteristics, applications, and efficiency of Class A, B, C, and D induction motors.
10. Explain how the speed of a wound rotor motor is controlled.
11. Explain how a rotating magnetic field is produced in each of the following single-phase induction motors:
    - a. Split-phase motors
    - b. Capacitor-start motors
    - c. Repulsion-induction motors
    - d. Shaded-pole motors
12. Compare the starting torques of the motors in the above objective and state an application of each type.
13. Explain the characteristics of capacitor-run, single-phase, induction motors that make them popular in sizes of 1-5 hp.
14. Explain, briefly, three methods of changing the speed of a single-phase induction motor.
15. Explain two methods of changing the speed of a universal motor. List an application employing each method.
16. Given the appropriate equipment, operate the following motors in the laboratory:
    - a. Universal motor with speed control
    - b. Shaded-pole motor with speed control
    - c. Capacitor-start motor with and without load

THREE-PHASE A.C. MOTORS

ROTATING MAGNETIC FIELDS

Figure 1 shows the location and connections of the field coil of a three-phase a.c. motor. Two complete cycles of the three currents through the stator coils are shown in Figure 2. Figure 3 shows the resulting magnetic field at the times indicated by numbers corresponding to the same numbers in Figure 2. For example, at time "0," current (conventional) flows into the stator on line 1 and out on lines 2 and 3, producing the magnetic field shown in part "0" of Figure 3. One-twelfth of a cycle later — at time "1" — current flows in on line 1 and out on 3 only, producing a field that has rotated clockwise, as shown in part "1" of Figure 3. As time passes, the magnetic field of the



a. CONNECTIONS

b. SCHEMATIC

Figure 1. Stator Windings of Three-Phase a.c. Motor.

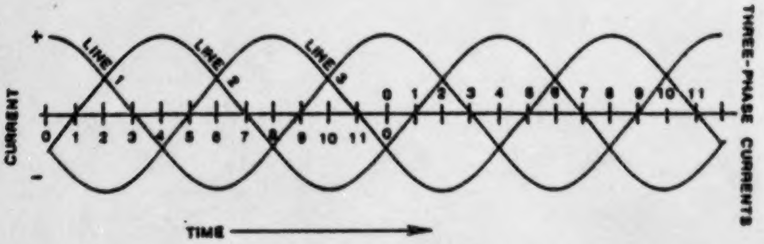


Figure 2. Two Complete Cycles of Current Form in a Three-Phase Machine.

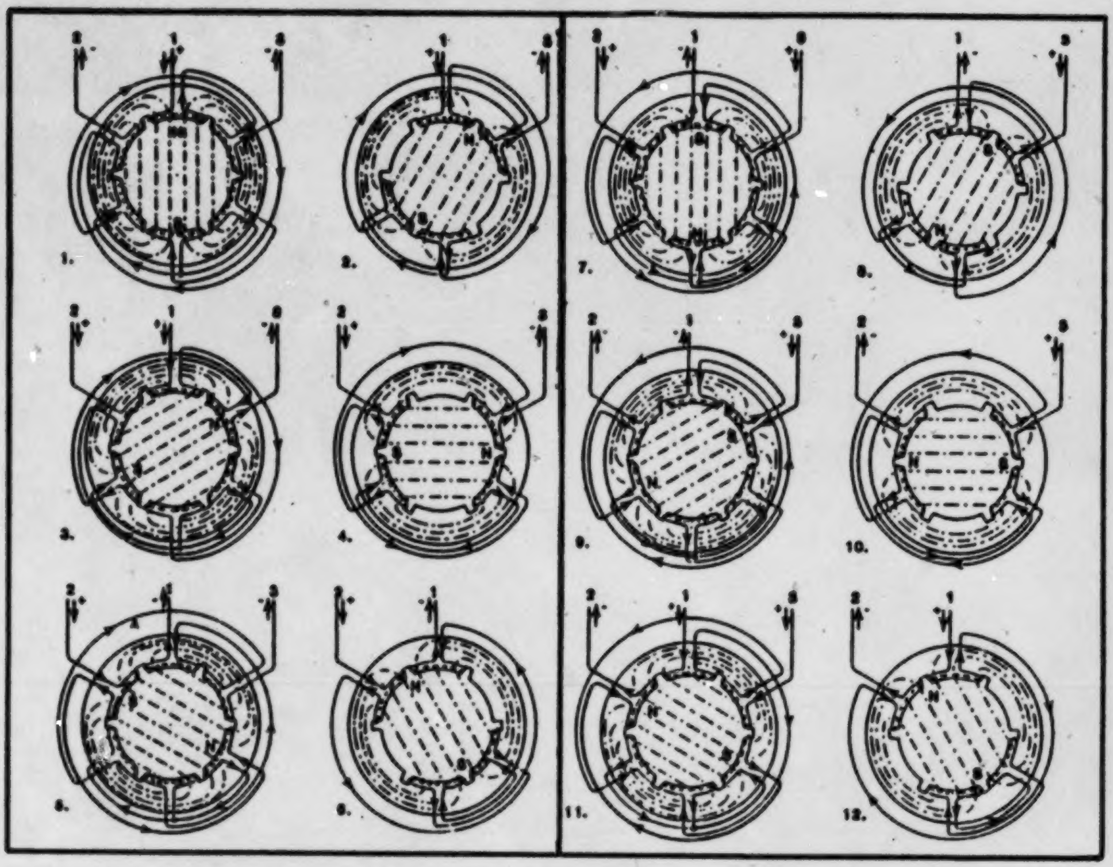


Figure 3. Electric Current and Magnetic Conditions in a Two-Pole, Three-Phase Motor for Each 30° of a Complete Cycle.

stator continues to rotate, making one complete revolution for each cycle of the applied three-phase current. This rotating magnetic field is the basis of operation of all three-phase a.c. motors.

SYNCHRONOUS MOTORS

A synchronous motor is formed by placing a rotating magnet inside the stator. The rotating magnet locks in step with the rotating field and makes one complete rotation for each complete cycle of the applied a.c. voltage. Thus, motor rotation is synchronized with the applied voltage, and the motor runs at a constant speed equal to the applied frequency. Synchronous motors can be constructed to rotate at an integral fraction of the applied frequency by including additional sets of stator coils and additional pole pairs on the rotor. A motor with three stator coil sets and three pole pairs on the rotor (a "six-pole" motor) has a speed equal to one-third of the applied frequency. The stator of this motor is wound to have a magnetic field with six poles that rotate at one-third of the applied frequency. For a 60-Hz driving voltage, such a motor will rotate 20 times per second, or at 1200 rpm.

INDUCTION MOTORS

An induction motor is found by placing a closed conducting loop inside the stator. A simple single-phase induction motor is shown in Figure 4. The rotating magnetic field induces a current in the closed loop and, thus, magnetizes the rotor. The induction motor operates on the same principle as a transformer. The transformer primary is the stationary stator winding; the secondary is the closed loop conductor of the rotor. The magnetic forces between the stator field and the rotor field cause the rotor to turn in the direction of rotation of the field in the three-phase induction motor.

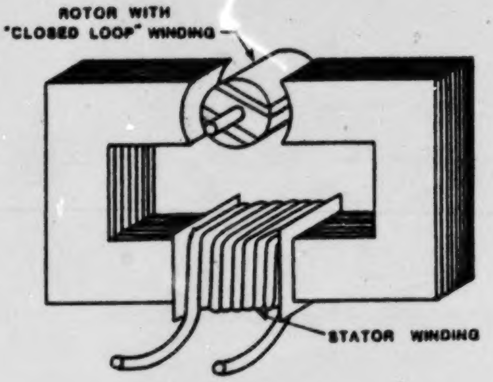


Figure 4. Simple Motor.

An induction motor does not rotate at synchronous speed. The rotor magnetic field depends upon the a.c. current induced in the rotor coils by the transformer action of the varying (rotating) magnetic field of the stator. If the rotor reaches synchronous speed, it no longer experiences a varying magnetic field. At synchronous speed, the rotor magnetic field is constant, and no current is induced in the rotor. The strength of the rotor field decreases, and the rotor "slips" with respect to the rotating field. As the rotor slows slightly, it is once again subject to a varying magnetic field, and a low frequency a.c. current is induced in the rotor coils. The difference in the synchronous speed of the motor and the actual speed is called the "slip speed"; this is between 1 and 5% of synchronous speed for most induction motors. Induction motors are usually rated in terms of synchronous speed; thus, an 1800 rpm induction motor will actually have a speed of 1 to 5% less than 1800 rpm (1710-1782 rpm). Like synchronous motors, the synchronous speed of an induction motor is determined by the number of coil sets in its stator and corresponding pole pairs in its rotor.

Motors are classified according to the number of poles (twice the number of pole pairs) on the rotor. The synchronous speed of a motor is given by Equation 1.

$$S_{syn} = \frac{120\ f}{N} \qquad \text{Equation 1}$$

where: S_{syn} = Synchronous speed in rpm.
f = Driving frequency in Hz.
N = Number of poles.

Example A shows the use of this equation in solving a problem.

EXAMPLE A: SPEED OF AN INDUCTION MOTOR.	
Given:	A three-phase, 12-pole, 60-Hz induction motor has a slip speed of 3% of its synchronous speed.
Find:	Operating speed.
Solution:	$S_{syn} = \frac{120\ f}{N}$ $= \frac{120\ (60)}{12}$ $S_{syn} = 600$ rpm $S_o = S_{syn} - S_{slip}$ $= 600$ rpm $- (0.03)(600$ rpm$)$ $= 600$ rpm $- 18$ rpm $S_o = 582$ rpm

POWER FACTOR IN A.C. MOTORS

In a.c. circuits, the power factor is the cosine of the phase angle between the voltage and the current in the circuit. The apparent power of the circuit is the product of voltage and current and is the vector sum of true power and reactive power. True power in a motor is the power that is converted to mechanical energy or heat energy. Reactive power is power that is accepted from the power source during part of the cycle and returned during another part of the cycle. The relationship of apparent power, true power, reactive power, and power factor is shown in Figure 5.

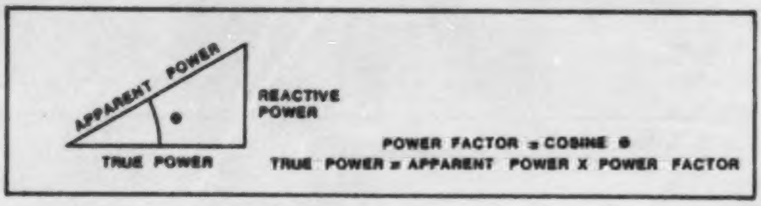


Figure 5. The Power Triangle.

If current and voltage are in phase, the power factor is 1 and the reactive power is zero. If current and voltage are out of phase, the power factor is less than 1. At a constant applied voltage, reducing the power factor means that greater current is required to produce the same true power. This current increase causes additional heating of conductors and reduces system efficiency.

If the current leads the voltage, the power factor is said to be "leading." If the current lags the voltage, the power factor is said to be "lagging." Induction motors always have lagging power factors because the rotor currents are induced by the stator fields. The power factor of a large high-speed induction motor is about 0.87 lagging. Smaller motors and slower motors have lower power factors. The power factors of synchronous motors can be varied by varying the strength of the rotor magnetic field.

SYNCHRONOUS MOTORS

ROTOR CONSTRUCTION

The rotor magnetic field of synchronous motors is produced by d.c. current flow through coils of the rotor. These coils are connected to an external d.c. supply by means of continuous slip rings and brushes. The rotor of a synchronous motor is constructed in the same way as an alternator rotor. (See Module EM-04, "Generators and Alternators.")

Two possible configurations of rotors are shown in Figure 6. The salient-pole rotor has field poles bolted to a cylinder on a shaft. The coils are wound on the poles and connected in series. The nonsalient-pole rotor has

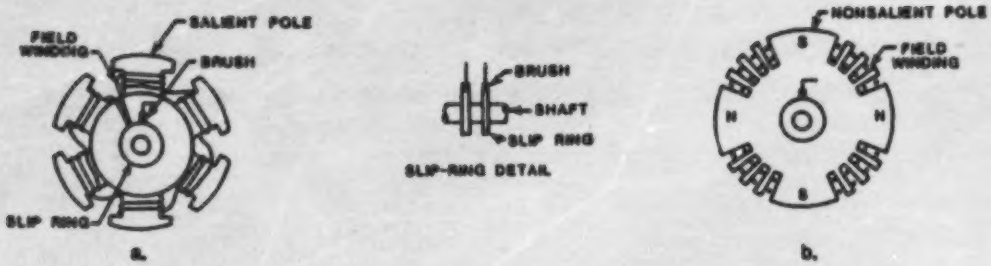


Figure 6. Salient-Pole and Nonsalient-Pole Rotors.

field windings set in slots in the solid rotor core. The nonsalient-pole rotor is usually used for two-pole and four-pole rotors. Rotors with six or more poles are usually the salient-pole type.

If the mechanical load of a synchronous motor is suddenly increased, the rotor slows slightly. The stator current increases to increase torque, and the rotor accelerates. If the acceleration is too great, it will "overshoot" the synchronous position and begin to slow again. This oscillation in speed is called "hunting"; it can damage the motor and result in large current surges.

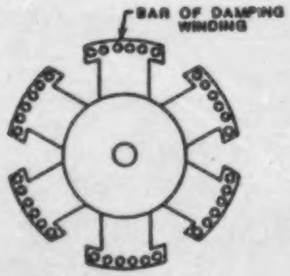


Figure 7. Salient-Pole Rotor with Damping Winding.

Hunting can be minimized by the use of damping windings, as shown in Figure 7. Damping windings are actually solid copper bars that extend through the rotor poles. Each end of the bars is connected to a continuous copper ring (not shown) to form a "squirrel-cage" winding similar to those used in induction motors and described later in this module. If the rotor turns at synchronous speed, no current is induced in the damping coils, and they have no effect. If the rotor slows, even slightly and momentarily, the large currents induced in the damping coils provide a torque pulse that moves the rotor back toward the synchronous position. If the rotor overshoots, the induced currents reverse to produce a torque that slows the motor slightly.

FIELD EXCITATION AND POWER FACTOR

The rotor field of a synchronous motor can be excited by an external d.c. power supply, by a d.c. generator run by an a.c. induction motor, or by a directly-connected d.c. generator called an "exciter." Large synchronous motors are usually directly excited. Such a motor is shown in Figure 8.

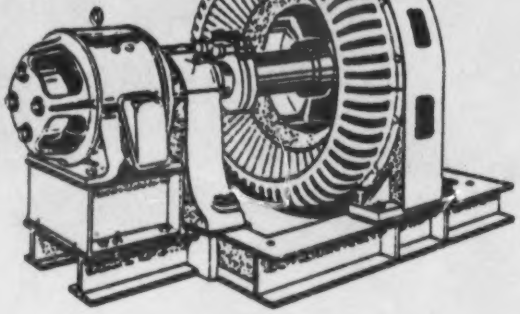


Figure 8. Synchronous Motor with a Directly-Connected Exciter.

Varying the rotor current does not change the true power of a synchronous motor, but it does change the power factor and the stator current. Figure 9 shows stator current versus field current for a synchronous motor under several load conditions. At low field currents, the current lags the voltage as in an induction motor. At higher field currents, the current leads the voltage.

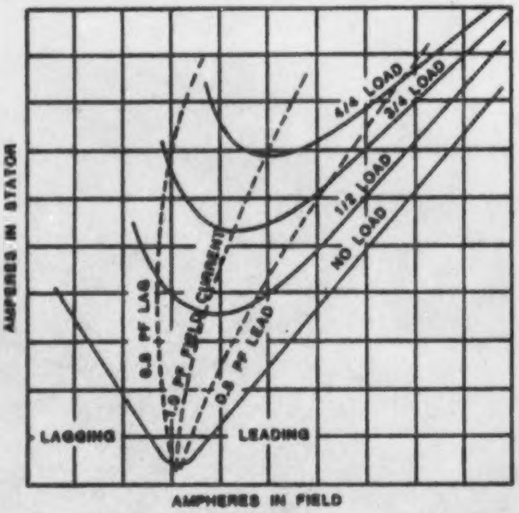


Figure 9. Typical V-Pattern Characteristics of a Synchronous Motor.

The rated field current of a synchronous motor is the current that produces a power factor of 1.0 at full mechanical load. Figure 9 shows that a reduction of load requires a reduction of field current to maintain maximum power factor and maximum motor efficiency. If a synchronous motor is to be operated at reduced load for long periods of time, its field current should be adjusted to the value producing the minimum stator current (PF = 1.0) for that load.

In some plants, the same power delivery system provides electrical power to both synchronous motors and induction motors or other "lagging" loads. In those cases, the synchronous motor field current can be increased to give a leading power factor that compensates for lagging power factors elsewhere in the system. This will lower the motor efficiency, but it will reduce current in the delivery system and may increase total plant efficiency.

STARTING SYNCHRONOUS MOTORS

A pure synchronous motor develops torque only at or near synchronous speed; it has no starting torque. In a directly-excited synchronous motor, the d.c. generator can be operated as a d.c. motor to bring the synchronous motor to near synchronous speed. The synchronous motor is then energized and will pull into synchronization and operate at constant speed.

A more common practice is to use the damping coils as induction coils and start the synchronous motor as an induction motor. Any of the methods described later in this module for starting induction motors may be used. The motor must reach 95% of synchronous speed before the rotor field is energized. Exciting the field too soon will cause the motor to act as an alternator, producing current surges in the stator coils and their supply lines.

Synchronous motors are often designed with induction windings that can start the motor under full load. Figure 10 shows characteristic curves of such a motor. The torque and current curves shown are for induction motors starting with a rotor current of zero. The pull-in torque is the torque value that is supplied by the synchronous motor when its rotor is energized. The motor then achieves synchronous speed, and the induction torque drops to zero. The pull-out torque is the maximum torque that the motor can deliver without being pulled out of synchronization. If this torque value is exceeded, the motor will slow. This can result in motor damage.

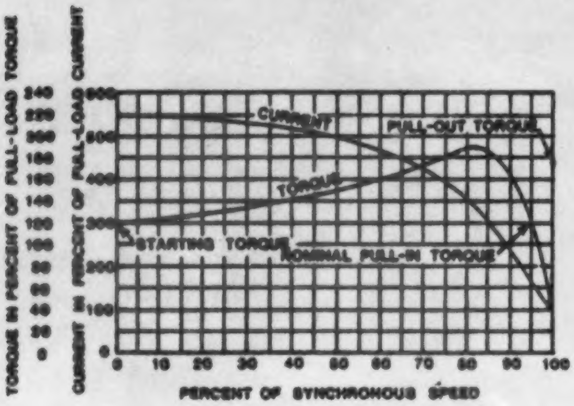


Figure 10. Speed-Torque and Speed-Current Characteristics of a Typical, High-Speed Synchronous Motor.

If the rotor current of a synchronous motor is interrupted, the motor will slow and continue to run as an induction motor. Prolonged operation as an induction motor will cause the rotor to overheat, damaging the windings. The rotor field should not be re-energized if motor speed is less than 95% of synchronous speed.

APPLICATIONS OF SYNCHRONOUS MOTORS

Synchronous motors are rarely used in sizes below 20 hp, and most are 100 hp or more; they provide maximum efficiency for constant load, constant speed operation. In a system employing induction motors, synchronous motors can be run with a leading power factor to improve system power factor.

High-speed synchronous motors (above 500 rpm) are used to drive centrifugal pumps and compressors, d.c. generators, fans and blowers, and belt-driven reciprocating compressors. Low-speed synchronous motors (under 500 rpm) are used to drive reciprocating compressors (largest field of use), screw-type pumps, metal rolling mills, and a variety of industrial devices requiring constant speed and torque.

Small single-phase synchronous motors of several types are used as clock motors and in other timing applications. The motors are made so they start as shaded-pole induction motors (discussed later in this module), but when they reach synchronous speed, their rotor cores maintain a particular magnetic polarity because of hysteresis. The poles of the rotor then lock into step with the pulsating stator field. Such motors typically require only about three watts of electrical input power.

THREE-PHASE INDUCTION MOTORS

ROTOR CONSTRUCTION

The simplest and most common type of rotor in induction motors is the squirrel cage rotor shown in Figure 11. It consists of bare copper bars brazed to copper end rings. Large currents are induced in the low-resistance bars. No insulation is necessary because the varnish between laminations of the rotor core prevents current flow through the core. In small induction motors, the rotor may be cast aluminum, as shown in Figure 12. The conducting bars are often skewed as shown in the figure to provide a more uniform torque and to reduce the magnetic vibrations present if the bars are parallel to the motor shaft.

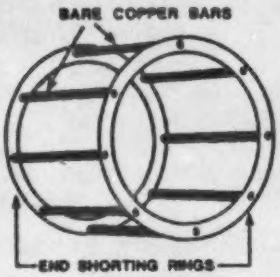

BARE COPPER BARS
END SHORTING RINGS

Figure 11. Squirrel Cage Motor Rotor.

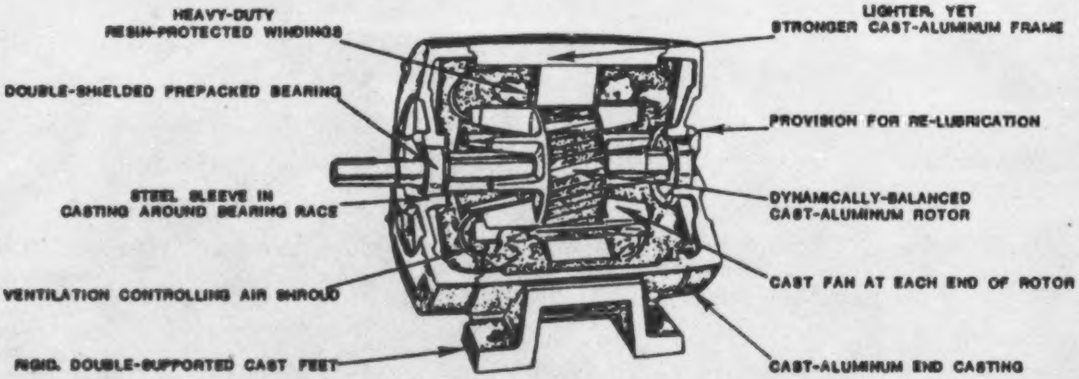

HEAVY-DUTY RESIN-PROTECTED WINDINGS
DOUBLE-SHIELDED PREPACKED BEARING
STEEL SLEEVE IN CASTING AROUND BEARING RACE
VENTILATION CONTROLLING AIR SHROUD
RIGID, DOUBLE-SUPPORTED CAST FEET
LIGHTER, YET STRONGER CAST-ALUMINUM FRAME
PROVISION FOR RE-LUBRICATION
DYNAMICALLY-BALANCED CAST-ALUMINUM ROTOR
CAST FAN AT EACH END OF ROTOR
CAST-ALUMINUM END CASTING

Figure 12. Squirrel Cage Rotor in an Induction Motor.

ROTOR RESISTANCE AND MOTOR CHARACTERISTICS

Figure 13 shows the torque speed curves of three induction motors with different rotor resistances.

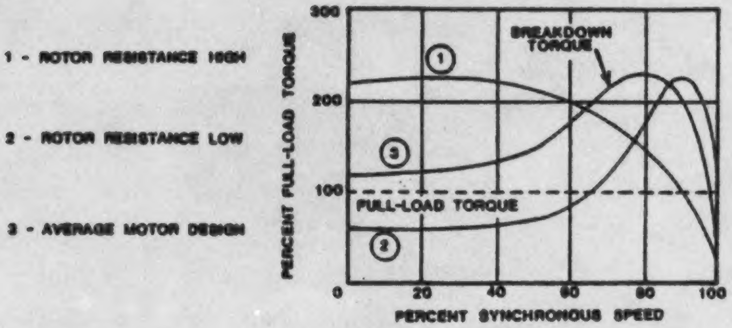


Figure 13. Torque Speed Curves of Three Induction Motors.

Curve 1 is for a motor with high rotor resistance. This motor produces high starting torque. Its high rotor resistance limits the rotor starting current and, thus, limits stator starting current. This type of induction motor can be started by connecting it directly to the a.c. power line. The high rotor resistance causes a large slip speed and low motor efficiency. The speed of this motor changes considerably as motor load changes.

Curve 2 is for a motor with a low rotor resistance. This motor produces a low starting torque. Its starting current is high, and it can be started with reduced current and voltage, as described in the following section of this module. The slip speed of this motor is low under full load, and it operates at almost synchronous speed. The low rotor resistance makes this the most efficient type of induction motor. Most large induction motors are of this type.

Curve 3 is for a motor with moderate rotor resistance. Its characteristics are a compromise between the two extremes. Induction motors are available with a wide variety of characteristic curves, each suited to a particular type of application and each having a particular rotor configuration. A complete discussion of rotor design is beyond the scope of this module.

STARTING THREE-PHASE INDUCTION MOTORS

Induction motors with high rotor resistance (curve 1 of Figure 13) are usually started by connecting the motor directly to an a.c. source at the rated voltage of the motor. The rotor resistance limits starting current to 200 to 300% of running current, and the high starting torque accelerates the motor rapidly to running speed. Motors with low rotor resistance can usually be started "across-the-line" if the line can deliver starting currents that are about 600% of running current.

Induction motors are sometimes started by some means that limit current during starting. The following methods can be used:

- Resistors can be placed in series with the three-phase power lines to limit current.
- A three-phase variable autotransformer can be used to reduce applied starting voltage. Multiple-tap transformers can also be used.
- Inductors can be placed in series with the three-phase power lines to limit starting current.
- The rotor can have two sets of windings — a high resistance set for starting and a low resistance set that is connected after the motor has reached running speed.

These techniques are also used to start synchronous motors with induction windings.

APPLICATIONS OF THREE-PHASE INDUCTION MOTORS

Three-phase induction motors are the most widely-used motors in powers of 5 hp and above. As previously mentioned, they can be designed with a wide range of operating curves. The National Electrical Manufacturers Association (NEMA) has established classifications of induction motors as the following types:

- Class A — Normal torque, normal starting current motors (highest efficiency
- Class B — Normal torque, low starting current motors
- Class C — High torque, low starting current motors
- Class D — High-slip motors (lowest efficiency)
- Class E — Low starting torque, normal starting current motors
- Class F — Low starting torque, low starting current motors

Most induction motors are in the first four classes. The torque curves of these motors are shown in Figure 14.

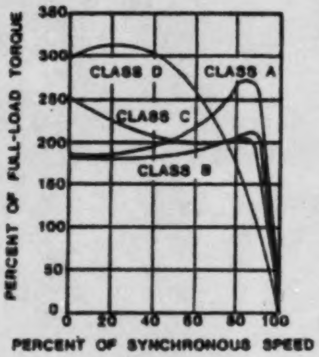


Figure 14. Typical Torque-Speed Curves for 1800-rpm General-Purpose Induction Motors.

Class A motors are the most common type. They are used to drive low inertia loads that can accelerate to full speed in a few seconds in applications requiring infrequent motor starting. These include fans, pumps, compressors, and conveyors. Class A motors can be severely overheated if started several times by across-the-line starting in a few minutes.

Class B motors are used when the power delivery system cannot provide the high currents required to start Class A motors and when motor starting is more frequent. Class C motors are used when higher starting torques are required with low starting currents, as in some compressors. Class C motors have lower efficiency than Class A or B. Class D motors provide the highest starting torque, but they are usually too inefficient for continuous operation.

The power factor and efficiency of an induction motor are lower at lower motor loads. Motors are designed for maximum efficiency at the rated load and can operate safely with a small overload at only a small loss in efficiency. High-speed motors generally have lower cost and weight and higher efficiency than low-speed motors. For greatest efficiency, the motor should be carefully selected to match the load.

WOUND ROTOR MOTORS

Figure 15 shows the rotor of a wound rotor induction motor. The rotor windings are connected to three slip rings, which are connected to an external resistance circuit by means of brushes. The control circuit of a wound rotor motor is shown in Figure 16.

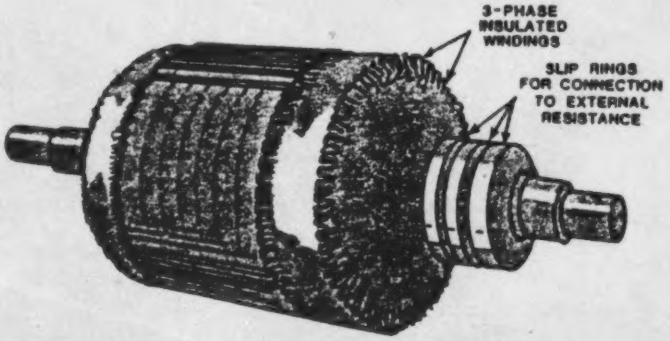

3-PHASE INSULATED WINDINGS
SLIP RINGS FOR CONNECTION TO EXTERNAL RESISTANCE

Figure 15. A Wound Rotor.

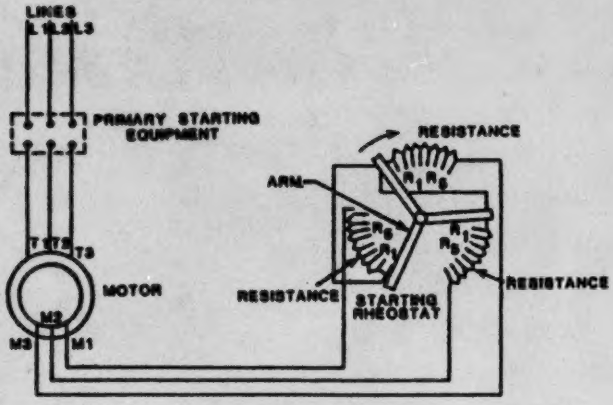


Figure 16. Diagram of a Starter, or Controller, for a Wound Rotor Induction Motor.

The wound rotor motor is started by connecting it to a three-phase power source with the control circuit set for maximum resistance. The motor speed can be adjusted over a wide range by changing the resistance of the control circuit. This does not provide constant speed for variable loads. At minimum resistance, the motor runs near synchronous speed for any load within its rated range. At large resistance, the motor runs at only a fraction of synchronous speed, and the speed varies greatly as load varies.

Wound rotor motors are used whenever speed control or extremely high starting torques are necessary.

SINGLE-PHASE INDUCTION MOTORS

Single-phase induction motors (the most common type of electric motors) have running characteristics similar to the three-phase induction motors discussed above, but special techniques are required to start single-phase motors. A single-phase a.c. current produces an alternating magnetic field, but the field does not rotate. Once the induction motor rotor is turning, the alternating field delivers pulses of power that produce the motor torque; but the pulsating power will not start the motor. The rotor will begin to turn only if the magnetic field rotates.

Virtually all a.c. motors of 1 hp or less are single-phase induction motors. They are classified according to the method used to produce the rotating magnetic field that starts the motor.

SPLIT-PHASE MOTORS

Figure 17a is a diagram of a split-phase motor. The schematic diagram of this motor is shown in Figure 17b. The split-phase motor has two sets of stator coils. The running coils have low resistance and high inductance at starting. The starting coils have higher resistance and lower inductance. The currents through the two coil sets are shown in Figure 18. The starting coil current leads the running coil current. Thus, the magnetic field rotates from the starting coil poles toward the running coil poles, providing a typical starting torque of 200% of the running torque. When the motor reaches 75-80% of the synchronous rate, the centrifugal starting switch opens to break the starting coil current. In resistance-start motors, a resistor is added in series with the starting coil to produce a greater phase difference between the two currents.

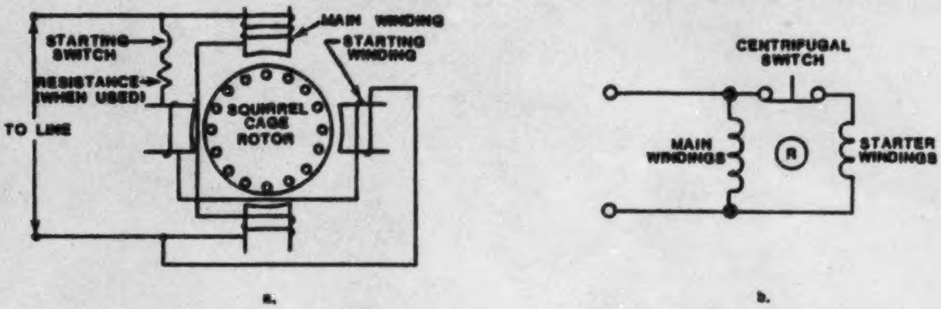

MAIN WINDING
STARTING SWITCH
STARTING WINDING
RESISTANCE (WHEN USED)
TO LINE
SQUIRREL CAGE ROTOR
a.
CENTRIFUGAL SWITCH
MAIN WINDINGS
R
STARTER WINDINGS
b.

Figure 17. Diagram of a Split-Phase Induction Motor.

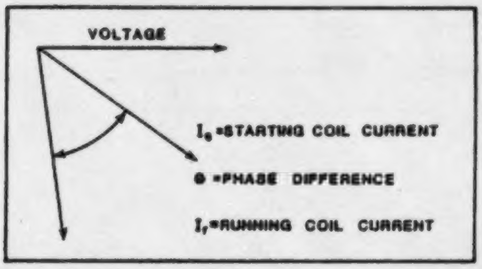

VOLTAGE
I_s =STARTING COIL CURRENT
θ =PHASE DIFFERENCE
I_r =RUNNING COIL CURRENT

Figure 18. Currents in a Split-Phase Motor.

Split-phase motors are the most commonly used type, in sizes from 1/30 to 1/2 hp. Applications include fans, business machines, and buffing machines.

CAPACITOR-START MOTORS

Figure 19 is a schematic diagram of a capacitor-start motor. In this motor, a capacitor has been added in series with the starting coil. The

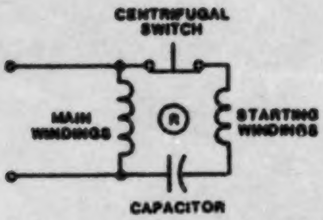


Figure 19. Capacitor-Start, Split-Phase Motor.

capacitive reactance exceeds the inductive reactance of the starting coil to produce a current through the starting coil that leads the voltage. This results in a starting coil current that is almost 90% out of phase with the running coil current at low motor speed. The high starting torque of a capacitor-start motor makes it ideal for compressors, vacuum pumps, larger fans, and a variety of shop equipment.

PERMANENT-CAPACITOR MOTORS

In permanent-capacitor motors, also called "capacitor-run" motors, the starting coil remains in the circuit as an auxiliary running coil. This improves both motor torque and power factor. Capacitor-run motors usually have a second starting capacitor that is connected in parallel with the permanent capacitor to provide higher starting torque. This capacitor is removed from the circuit by a centrifugal switch after the motor has approached running speed. The higher torque, power factor, and efficiency of capacitor-run motors results in wide application in powers of 1 to 5 hp.

REPULSION-INDUCTION MOTORS

The rotor bars of the repulsion-induction motor are permanently attached to one end ring only. The other end of each bar is connected to a commutator. A pair of shorting brushes connect two bars only during starting, as shown in Figure 20. The rotor begins to turn in the direction that the brushes are displaced from the field pole axis — counterclockwise in Figure 20. When the motor approaches synchronous speed, a centrifugal shorting ring closes on the rotor bars to short them all together, as in a normal squirrel cage rotor.

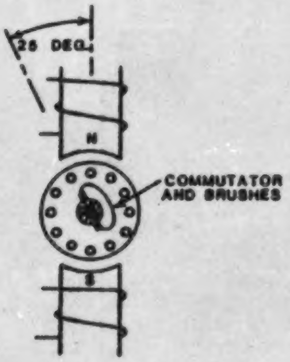


Figure 20. Repulsive Fields Built Up to Cause Motor to Start Rotation.

Repulsion-induction motors have torque curves similar to those of capacitor-start motors; however, they require lower starting currents. They are used in the compressors of refrigerators and in gasoline delivery pumps.

SHADED-POLE MOTORS

A "shaded pole" is produced by wrapping a single turn of heavy copper wire around a part of the pole face, as shown in Figure 21.

The operation of the shaded-pole motor is illustrated in Figure 22. In Figure 22a, the current through the field coil is increasing to produce an increasing magnetic field. This increase induces a current in the shading coil, producing a magnetic field in opposition to the main field and weakening the total field on the shaded side of the pole. In Figure 22b, the current through the field coil has reached a maximum. At this point, there is no change in magnetic field, and no current is induced in the field coil. The magnetic field is constant across the pole face. In Figure 22c, the field coil current is decreasing. The induced current in the field coil opposes the reducing field to make the field stronger on the shaded side of the pole. This shift in magnetic field strength is sufficient to start the motor if the load is light.

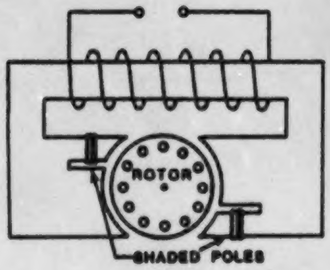


Figure 21. Two-Pole, Shaded-Pole Motor.

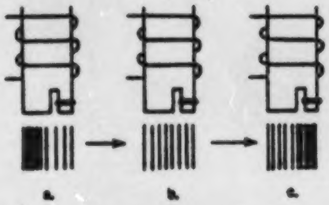


Figure 22. Field on Shaded Coil Moving from Left to Right.

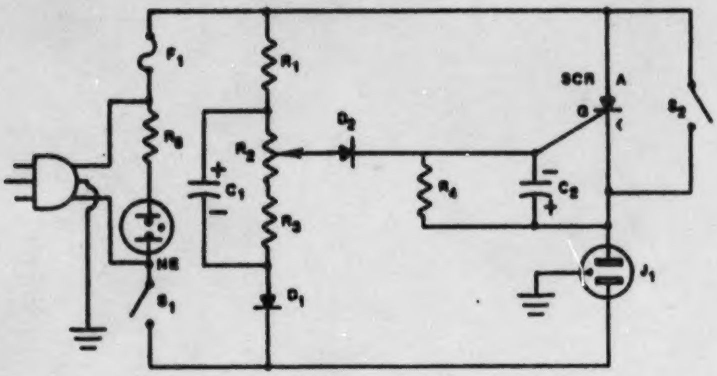
Shaded-pole motors produce very little starting torque, but they are common in small fans, electric clocks, and a variety of kitchen appliances.

SPEED CONTROL OF SINGLE-PHASE INDUCTION MOTORS

Fractional horsepower induction motors are often designed to run at more than one speed. The most common method of speed change is to switch the connections of field coils to change the number of magnetic poles in the stator field.

The speed of high-slip motors can be adjusted over a wide range by controlling the voltage applied to the motor and, thus, to the stator current. The most common method of voltage control is with an autotransformer with multiple taps.

The speed of many single-phase induction motors can be controlled by means of the SCR speed controller shown in Figure 23. Changing the setting of potentiometer R_2 changes the voltage at which the SCR begins to conduct. This controls the fraction of the cycle of the a.c. wave for which the line voltage is actually applied to the stator field of the motor. This type circuit is commercially available as a light dimmer control.



PARTS LIST FOR MOTOR SPEED CONTROL

R_1 – 2KΩ, 5W resistor
R_2 – 500Ω, 2W potentiometer
R_3 – 10Ω; 12W resistor
R_4 – 150Ω, 1/2W resistor
R_5 – 100Ω, 1/2W resistor
C_1, C_2 – 100μF, 25V electrolytic capacitor
NE – NE2 neon lamp
heat sink, 1/8 x 24-1/2 in. aluminum

D_1, D_2 – rectifier, Motorola HEP156 or RCA SK 3016
SCR – Motorola HEP302 or RCA SK 3557
F_1 – 3A, slo-blo fuse
J_1 – receptacle, Amphenol 61-F1
S_1, S_2 – SPST switch
fuse holder
a.c. plug, 3 wire

Figure 23. Schematic and Parts List for SCR Motor Speed Control.

UNIVERSAL MOTORS

Universal motors are series motors (see Module EM-05, "D.C. Motors and Controls") that can be operated with either a.c. or d.c. current. In the series motor, the armature (rotor) and field coils are connected in series. If an a.c. current flows through the motor, the current must be in phase in both windings. When the rotor current reverses, the stator current also reverses, and the two magnetic fields reverse directions in phase. Such a motor will operate equally well on a.c. or d.c. current.

Brush sparking is a serious problem in universal motors. It is reduced by using low inductance windings and by reducing current by placing resistors in series with the brushes.

The speed of universal motors varies greatly with load. Universal motors run at high speed with no load; however, unlike larger d.c. series motors, they cannot develop sufficient speed to damage the motor. If the load of a universal motor is constant, its speed can be varied continuously by a variable resistor in series with the motor. This method of control is used in sewing machines. Multiple speeds in appliances, such as blenders and mixers, are achieved by using multiple stator windings to change the magnetic field strength. Most vacuum cleaners and hand-held power tools also have universal motors.

EXERCISES

1. A 36-pole induction motor is operated on 60-Hz a.c. current and has a slip speed of 2.5% of synchronous speed. What is the rotational rate of the motor?
2. An induction motor operated on 115 V a.c. has a rotational rate of 1140 rpm. What is its slip speed? How many poles does the motor have?
3. A large synchronous motor has a rotor current that gives maximum motor efficiency (PF = 1.0) at full load. What happens to the power factor if the motor is operated at 1/4 load?
4. Identify the class of induction motor that would be best for driving the following loads. Explain the reason for each choice.
    a. A crane is used occasionally to lift heavy loads in a warehouse.
    b. A large centrifugal blower runs continuously for days at a time. The power delivery system does not limit starting current.
    c. An auxiliary blower identical to the one above is used only during peak loads. It may start several times in an hour under certain conditions. Because it only runs during peak power demands, its starting current is limited by the power delivery system.
5. Each student should count the number of electric motors in his or her home and identify the type of motor most likely used for each application.

6. Disassemble several electrical appliances and examine the motors.

LABORATORY MATERIALS

Blender with universal motor, 115 V a.c.
Small fan with shaded-pole motor, 115 V a.c., 0.9 A maximum
1/4 or 1/3 hp capacitor-start motor, 115 V a.c., with load such as a vacuum pump, compressor, or an air-conditioner blower
Starting capacitor for motor (see motor ratings)
Wattmeter, 0-1500 W
a.c. voltmeter, 0-150 V a.c.
a.c. ammeter, 0-20 A a.c.
a.c. ammeter, 0-1 A a.c.
Heavy-duty connecting wires
SCR light dimmer, 100 W, 115 V a.c., with power cord and recepticle
Stroboscope
DPST switch, 20 A, 115 V a.c.

LABORATORY PROCEDURES

CAUTION: EXPOSED CONDUCTORS IN THIS EXPERIMENT CARRY 115 V A.C. AND ARE A SERIOUS SHOCK HAZARD. DO NOT TOUCH ANY WIRES OR TERMINALS WHILE CIRCUITS ARE CONNECTED TO A POWER SOURCE.

1. Remove the bottom cover from the blender. Turn it upside down and inspect the motor and motor controls.
2. Plug in the blender power cord and operate the motor with the cover removed. Observe commutation and brush sparking at several speeds.
3. Unplug the blender.
4. Disassemble the blender motor. Label the location of each wire with a piece of tape attached to the wire. Sketch the parts of the blender motor in the Data Table.
5. Reassemble the blender and check it for proper operation.

6. Connect the dimmer switch, small fan motor, and 0-1 A ammeter, as shown in Figure 24.

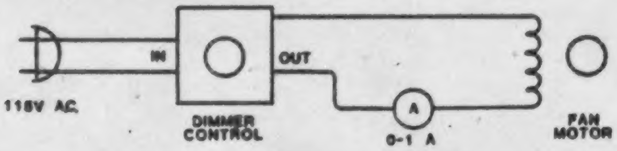

115V AC
IN
OUT
DIMMER CONTROL
A
0-1 A
FAN MOTOR

Figure 24. Experimental Fan Motor Circuit.

7. Plug in the power cord and use the dimmer control to vary fan motor speed.
8. Measure fan speed with the stroboscope at several values of motor current and record the data in the Data Table.
9. Unplug the power cord.
10. Disassemble the fan and motor. Sketch the parts of the fan motor in the Data Table.
11. Reassemble the motor and fan and check for proper operation.
12. Construct the circuit shown in Figure 25.

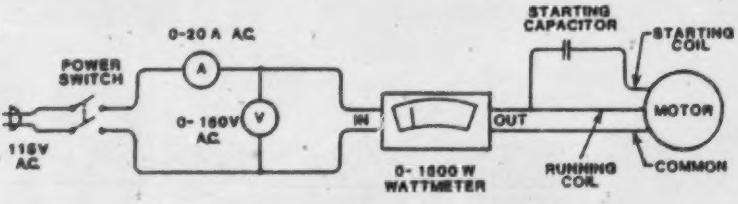

0-20 A AC
POWER SWITCH
A
0-150V AC
V
115V AC
IN
OUT
0-1500 W WATTMETER
STARTING CAPACITOR
STARTING COIL
MOTOR
RUNNING COIL
COMMON

Figure 25. Capacitor-Start Motor Circuit.

13. Plug in the power cord. With the motor load connected, close the power switch and observe the voltmeter and ammeter during motor starting. Describe their variations in the Data Table.
14. Record voltage, current, and power in the Data Table.
15. Measure motor speed with the stroboscope and record in the Data Table.
16. Turn off the power switch and disconnect the power cord.
17. Perform the necessary calculations and complete the section of the Data Table entitled "Running with Load."

18. Disconnect the motor from its mechanical load and repeat Steps 13 through 17 for no load.
19. Disassemble the motor and sketch its parts in the Data Table.
20. Reassemble the motor, reconnect it to its load, and check for proper operation.

DATA TABLE

DATA TABLE.

I. BLENDER MOTOR

Motor type ____________________

Sketches of motor parts:

Stator

Rotor

Commutator and brushes

II. FAN MOTOR

Motor type ____________________

Current (A)	Speed (rpm)

Sketches of motor parts:

Stator

Rotor

Data Table. Continued.

III. CAPACITOR-START MOTOR

A. Starting with load:

Describe current and voltage variations during starting with load.

B. Running with load:

Voltage: V_L = ___________ V

Current: I_L = ___________ A

True Power: P_T = ___________ W

Apparent Power: $P_A = V_L I_L$ = ___________ W

Power Factor: $PF = \frac{P_T}{P_A}$ = ___________

Synchronous Speed: S_{syn} = ___________ rpm

Operating Speed: S_o = ___________ rpm

Slip Speed: S_s = ___________ %

C. Starting with no load:

Describe current and voltage variations during starting with no load.

D. Running with no load:

Voltage: V_N = ___________ V

Current: I_N = ___________ A

True Power: P_T = ___________ W

Apparent Power: P_A = ___________ W

Power Factor: PF = ___________

Synchronous Speed: S_{syn} = ___________ rpm

Operating Speed: S_o = ___________ rpm

Slip Speed: S_s = ___________ %

Data Table. Continued.

E. Sketch the motor parts:

Stator

Rotor

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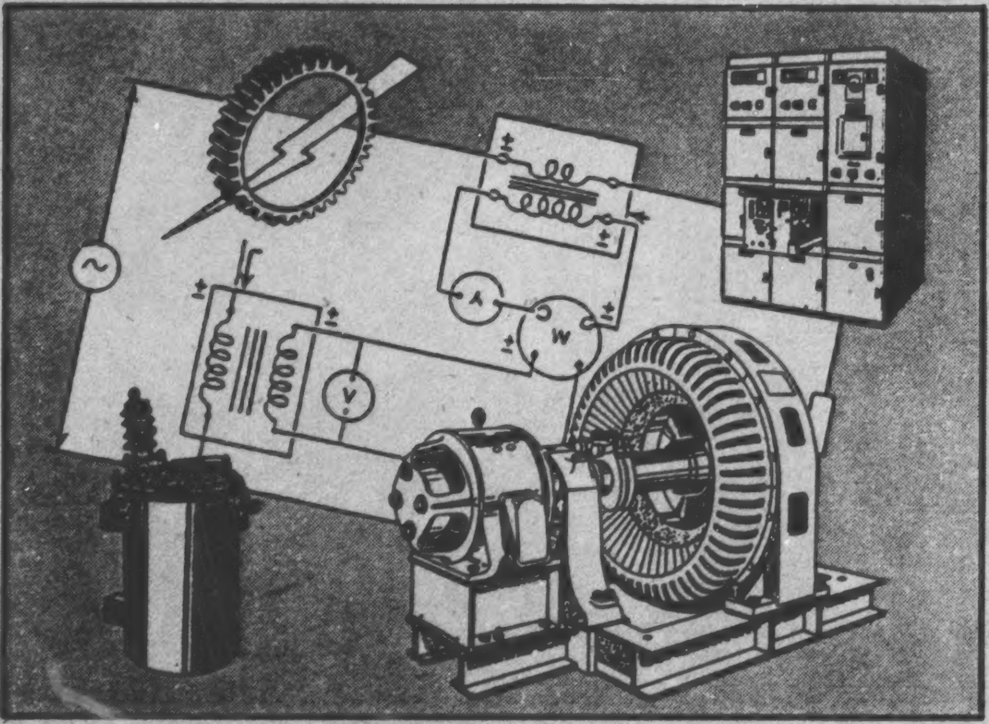
ENERGY TECHNOLOGY

CONSERVATION AND USE

ELECTROMECHANICAL DEVICES



MODULE EM-07

SYNCHROMECHANISMS

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Synchromechanisms are electromechanical devices used to position two shafts in the same angular position, to rotate two shafts in synchronization, and to produce a rotation of a controlled shaft that is the sum or difference of the rotation of two controlling shafts. Synchromechanisms serve the same function as gear trains but accomplish synchronization through the transmission of electrical signals rather than mechanical signals.

A synchro transmitter operates as a generator, converting mechanical input energy to electrical output energy. A synchro receiver operates as an electric motor and converts electrical energy to mechanical energy. A synchro transformer converts the electrical signal from a synchro transmitter into an electrical error signal that is used by a control circuit for positioning a shaft.

This module discusses the construction, operation, and application of the major types of synchromechanisms. In the laboratory, the student will construct a variety of self-synchronous control circuits.

PREREQUISITES

The student should have completed Module EM-06 of "Electromechanical Devices."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Draw and label a diagram showing the windings and connections of a synchro transmitter stator.
2. Draw and label a diagram of a synchro transmitter rotor.
3. Draw and label a diagram of the RMS values of the a.c. voltages on the three stator coils of a synchro transmitter as the rotor is turned through a complete revolution.
4. Explain the difference in construction of the rotors of synchro transmitters and receivers, and state the reason for that difference.

5. Given a diagram of a synchro transmitter-receiver pair showing the magnetic polarity of the transmitter rotor at one time, determine the magnetic polarity of the other coils at the same time.
6. Explain, with the use of diagrams, two methods of determining the electrical zero of a synchro transmitter or receiver.
7. Draw schematic diagrams of synchro transmitter-receiver pairs connected for the following directions of rotation:
    a. Transmitter and receiver shafts rotate in the same direction.
    b. Transmitter and receiver shafts rotate in opposite directions.
8. Draw and label a schematic diagram of a differential synchro transmitter showing all field and stator coils.
9. Draw and label simple diagrams of synchro systems with a transmitter, a differential transmitter, and a receiver connected to achieve the following:
    a. Output rotation is the difference of the input rotation angles.
    b. Output rotation is the sum of the input rotation angles.
10. Given a schematic of a system employing a differential synchro transmitter and the rotational rates and directions of the input shafts, determine the rotational rate and direction of the output shaft.
11. Draw and label a simple diagram of a synchro control transformer in an angular alignment system and explain how the system functions.
12. List the seven most common classes of synchromechanisms and the letter code for each.
13. Given the appropriate equipment, construct synchro control circuits in the laboratory and evaluate their performance.

THE SYNCHRO TRANSMITTER

The synchro transmitter is a generator that converts mechanical input energy into electrical output energy. Figure 1 shows the stator windings of a synchro transmitter. The stator contains three coils of wire that are located 120° apart around the stator and connected as shown with three external leads.

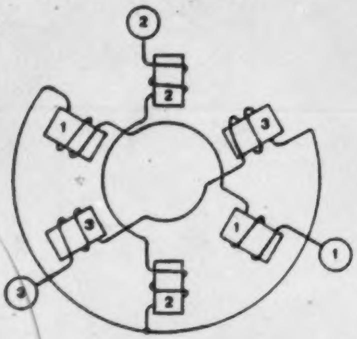


Figure 1. Windings and Connections of
a Synchro Transmitter Stator.

Figure 2 shows the rotor of the synchro transmitter. It consists of a single coil of wire wound around a rotor core with two salient poles. The coil is connected to an external a.c. current source through two continuous slip rings. Figure 3 is a cutaway view of an assembled synchro transmitter.

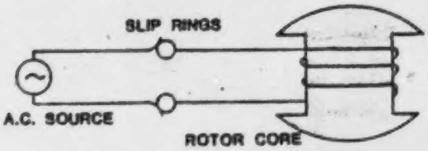

SLIP RINGS
A.C. SOURCE
ROTOR CORE

Figure 2. Synchro
Transmitter Rotor.

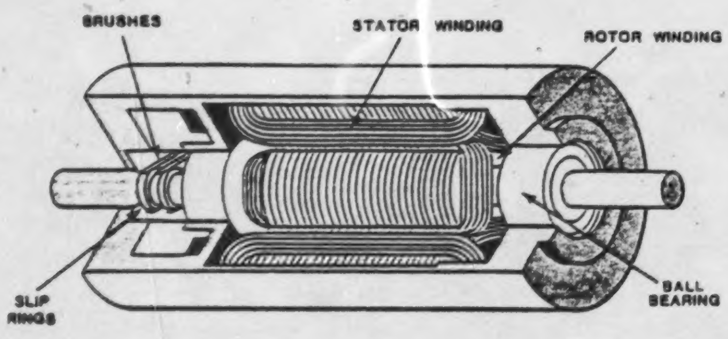

BRUSHES
STATOR WINDING
ROTOR WINDING
SLIP RINGS
BALL BEARING

Figure 3. Cutaway View of a Synchro Transmitter.

Two schematic representations of syncrho transmitters are shown in Figure 4. The diagram in Figure 4a is useful in describing the operation of a

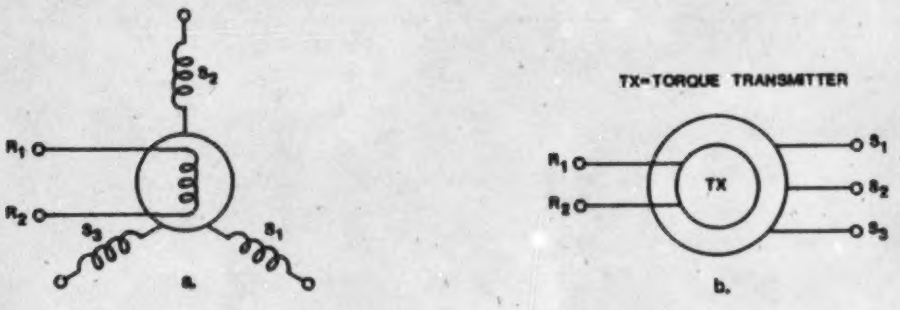


Figure 4. Schematic Representation of a Synchro Transmitter.

synchro; that in Figure 4b is more useful in synchro circuit design.

Figure 5 shows a synchro transmitter connected to an a.c. current source. The a.c. current flows through the rotor coil and induces a voltage in the three stator coils. In this figure, the maximum voltage is induced in stator coil 2 because the rotor coil is aligned with that stator coil. Lower voltages are induced in coils 1 and 3 because they are each 60° out of alignment with the rotor coil.

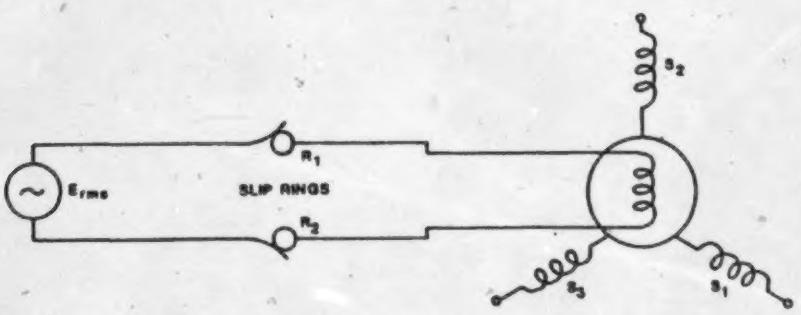


Figure 5. Power Source Connected to a Synchro Transmitter.

If the rotor is rotated by mechanical means to the position shown in Figure 6, the voltage induced in coil 2 drops to zero because the rotor coil is now perpendicular to that stator coil. Continuing the rotation through another 90° will align the rotor with coil 2 again, but the polarity will be opposite of that in Figure 5.

Figure 7 shows the voltage induced in coil 2 as a function of rotor angle. Vertical displacement represents the RMS value of the induced voltage. A

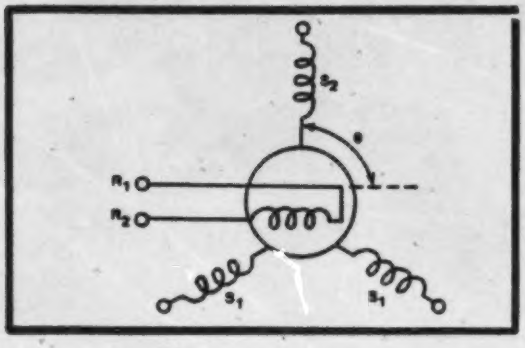


Figure 6. Clockwise Rotation of the Rotor.

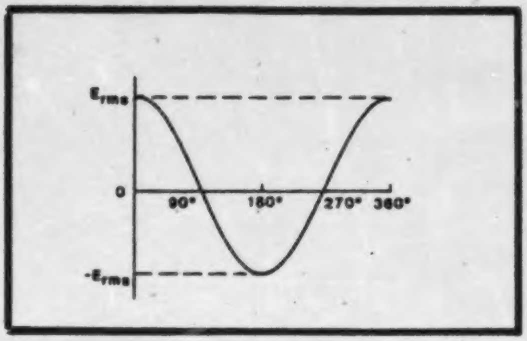


Figure 7. One Cycle of S_2 Voltage.

negative value of E_{rms} indicates that the polarity of the induced voltage in coil 2 is opposite that induced in Figure 5. Figure 8 is a similar diagram showing the induced voltages in all three coils. The three waves do not represent a three-phase voltage. They indicate the magnitude and polarity of the single-phase a.c. voltages induced in each of the three stator coils as the rotor is turned.

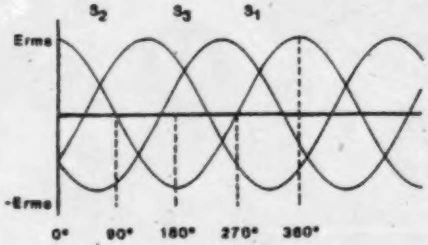


Figure 8. Induced Stator Voltages as Functions of Angle of Rotation.

The coil voltages cannot be measured directly with a voltmeter because only one end of each coil is connected to an external terminal. Thus, the voltage across any two output terminals is the sum of the voltages in two coils.

Individual coil voltages can be measured using the circuit shown in Figure 9. The three resistors are all the same size (typically about 5000Ω to

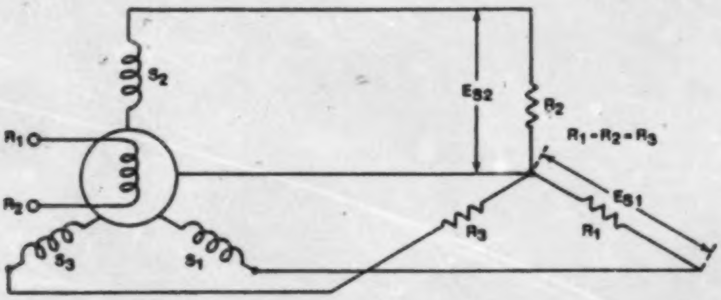


Figure 9. A Loaded Synchro.

limit current). The voltage across any one of the resistors can be measured with a voltmeter and is equal to the voltage of the corresponding coil.

The maximum voltage produced by a stator coil depends on the voltage applied to the rotor and the turns ratio of the two coils. One of the most common values of turns ratio is a 2.2:1 step-down ratio between the rotor and stator. With 115 V a.c. applied to the rotor, such a synchro transmitter will have a maximum stator coil voltage of 52 V a.c.

The electrical zero of a synchro transmitter is the rotor position in which the voltage between S_1 and S_3 is zero and the S_2 terminal voltage is in phase with the voltage on rotor terminal R_1. Two methods of locating the electrical zero of a synchro are shown in Figure 10. In Figure 10a, terminals S_1, S_3, and R_2 are connected together and terminals S_2 and R_1 are connected together. Applying an a.c. voltage across the rotor will cause it to line up as shown at electrical zero. The full rotor voltage should not be applied when using this method, as it could produce currents that will damage the stator coils.

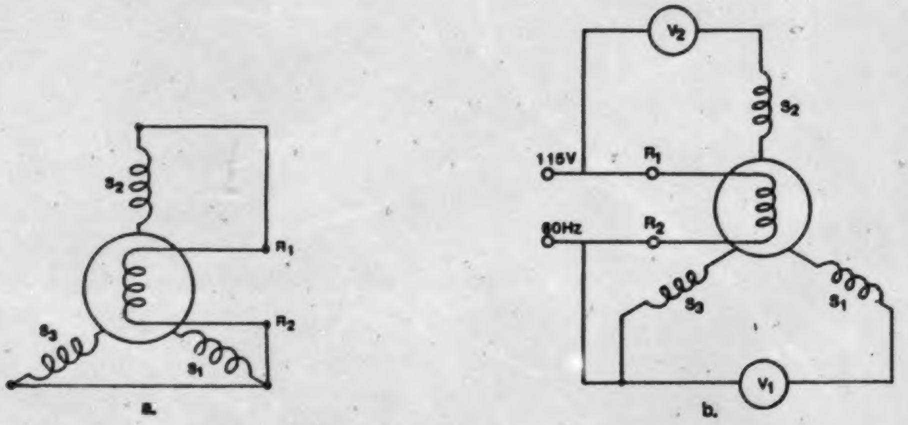


Figure 10. Two Methods of Determining Electrical Zero.

Figure 10b illustrates the voltmeter method of determining electrical zero. The rotor is in the electrical zero position when V_1 is zero and V_2 is less than the line voltage.

These same methods of locating the electrical zero can also be used for the synchro receiver discussed in the following section.

THE SYNCHRO RECEIVER

The synchro receiver is a motor that converts the electrical energy output from a synchro transmitter back into mechanical energy. Figure 11 shows the rotor of a synchro receiver. The only difference in the synchro transmitter and the synchro receiver is the inertia damper on the receiver rotor.

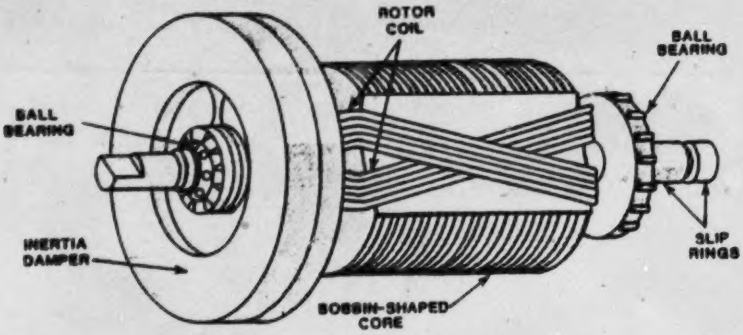

ROTOR COIL
BALL BEARING
BALL BEARING
INERTIA DAMPER
SLIP RINGS
BOBBIN-SHAPED CORE

Figure 11. Rotor of Synchro Receiver.

The inertia damper is a weighted wheel; its large moment of inertia prevents abrupt changes in rotor position or speed, therefore reducing the tendency of the synchro receiver to oscillate.

The electrical symbols of the receiver are the same as those of the transmitter. Figure 12 shows a synchro transmitter and receiver in a self-synchronous control system. The rotors of the two are connected to the same power source. Like coils of each synchro are connected together. The same circuit is shown another way in Figure 13.

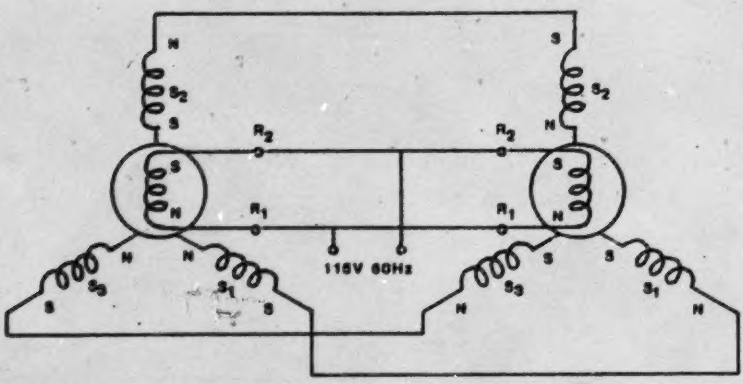

N
S_2
S
S
S_2
N
R_2
R_2
S
N
R_1
R_1
S
N
N
N
S
S
115V 60Hz
S_3
S_1
S
S
S_3
S_1
N
N

Figure 12. A Synchro Pair.

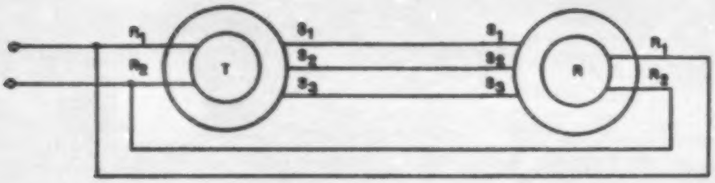


Figure 13. Transmitter-Receiver Pair.

Figure 12 also shows the polarity of the magnetic field of each coil at one instant of the applied a.c. voltage. The upper end of each rotor coil is a south pole. In the transmitter, the rotor field induces currents in the stator coils that produce fields opposing the rotor field. These same currents flow through the receiver coils to produce the magnetic polarities shown. The rotor of the receiver lines up with the stator field of the receiver. Both synchros are shown in the electrical zero position in Figure 12. The polarity of each coil reverses at the frequency of the applied voltage, but since all polarities reverse at the same time, the receiver rotor is held in place.

In Figure 14, the transmitter rotor has been rotated through an angle of 30°. This increases the current through S_3, decreases the current through S_2, and reduces the S_1 current to zero. Since the same currents flow through the receiver stator coils, the magnetic field of the receiver stator also rotates by 30°. The receiver rotor turns to align its field with the stator field. Alignment is never perfect because of friction in the motor bearings, but in most systems the receiver angle will be within one degree of the transmitter angle. In a system in which both shafts rotate continuously, the torque applied to the transmitter rotor is changed to electrical currents that produce

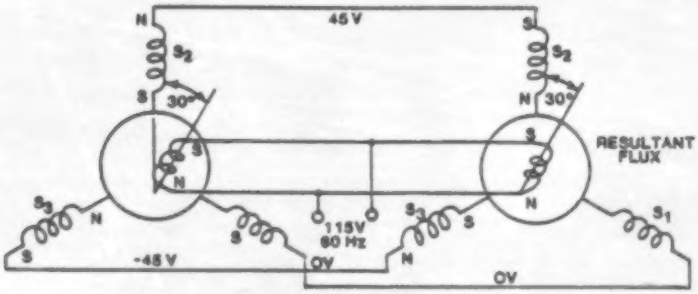


Figure 14. Magnetic Polarities.

torque in the receiver rotor. Since torque is produced in the receiver only when its rotor field lags behind its stator field, the receiver shaft position lags behind the transmitter shaft position by about 3° in continuously rotating torque transmitters.

If the rotor leads of one of the synchros are reversed, as shown in Figure 15, the receiver rotor will be 180° out of phase with the transmitter rotor.

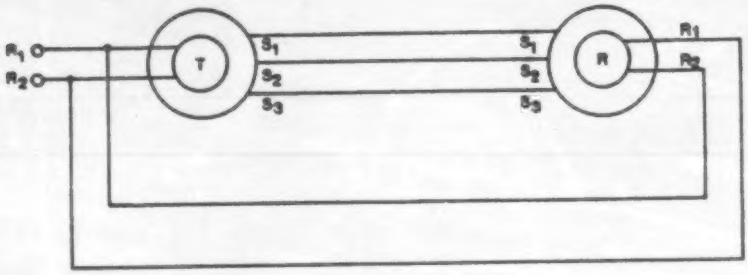


Figure 15. Rotor Leads Reversed.

If two of the stator connections are reversed, as shown in Figure 16, the receiver rotor will rotate in the opposite direction from the transmitter rotor.

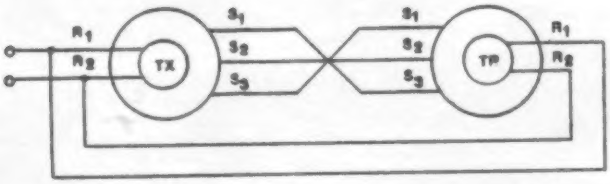


Figure 16. Stator Connections for Rotation in Opposite Directions.

DIFFERENTIAL SYNCHRO TRANSMITTERS AND RECEIVERS

Differential synchro transmitters (generators) and receivers (motors) are used with other synchro devices to produce an output shaft rotation that is the sum or difference of the angular rotations of two input shafts. The stator of the differential synchro is the same as for those already discussed. The differential synchro rotor contains three coils (and, thus, three pole pairs) connected as shown in Figure 17a. It can be represented schematically

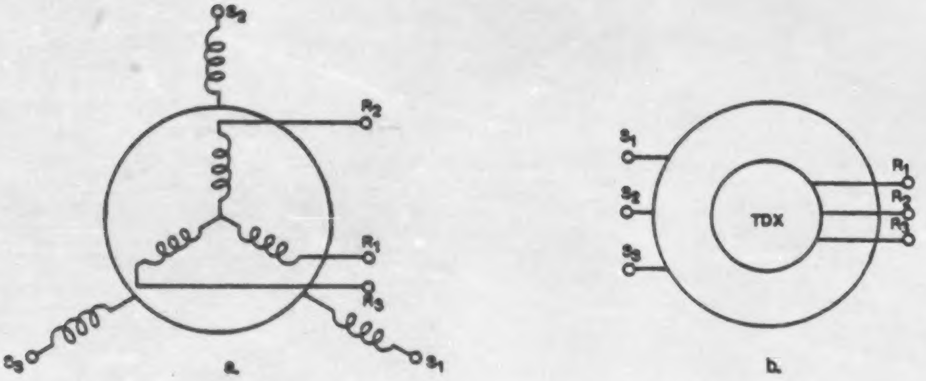


Figure 17. The Synchro Differential.

by the diagram in Figure 17b. The rotor of such a differential synchro transmitter is shown in Figure 18. The rotor of the receiver differs only in the addition of an inertia damper.

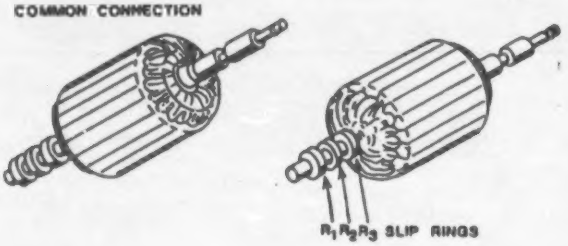


Figure 18. The Differential Rotor.

Figure 19a shows a control circuit employing a differential transmitter. The magnetic polarities of the S_2 stator coils and rotor coils at one instant of time are also shown. Figure 19b is a more convenient way to draw the same circuit. The action of this circuit is given by Equation 1.

$$\gamma = \alpha - \beta \qquad \text{Equation 1}$$

where: γ = Angle of rotation of output shaft of synchro receiver (TR).
α = Angle of rotation of input shaft of synchro transmitter (TX).
β = Angle of rotation of input shaft of differential transmitter (TDX).

In this equation, positive angles represent clockwise rotation. The use of this equation is illuatrated by the data in Table 1.

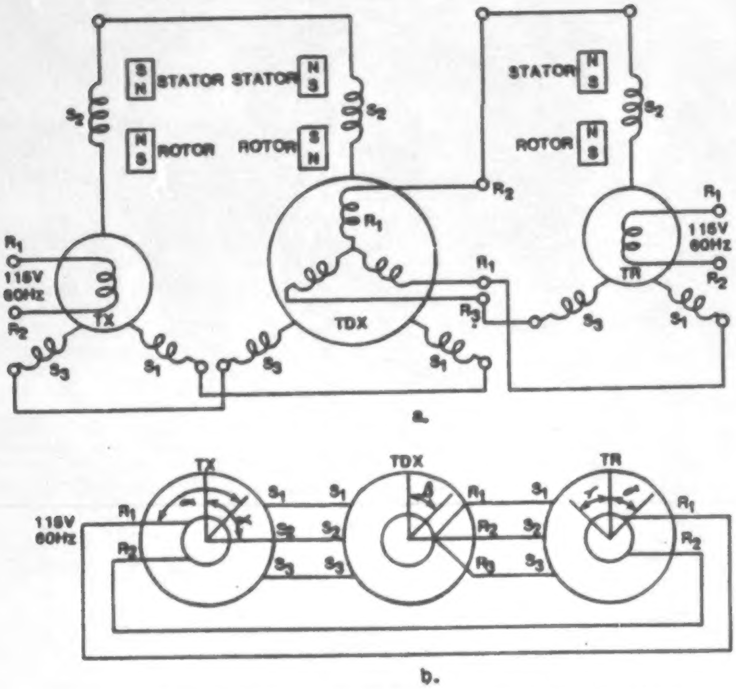


Figure 19. Control Circuit Employing Differential Transmitter.

TABLE 1. INPUT AND OUTPUT ANGLES OF A DIFFERENTIAL SYNCHRO SYSTEM CONNECTED FOR ANGULAR SUBTRACTION (Angles in Degrees).

Input Angles		Output Angle
α (TX)	β (TDX)	γ (TR)
45	45	0
45	0	45
0	45	-45 (CCW)
45	-45 (CCW)	90
-45 (CCW)	45	-90 (CCW)

If the system in Figure 19 is operated on a continuous basis, the rotational rates of the shafts have the same relationship as those for the angles given in Equation 1. The rotational rate of the output shaft is the difference in the rates of the input shafts with clockwise rotation defined as positive. Example A illustrates the use of Equation 1 in solving a problem.

EXAMPLE A: OUTPUT SPEED OF DIFFERENTIAL SYNCHRO CIRCUIT.

Given: In the synchro circuit in Figure 19, the input rotational rates of the transmitter and the differential transmitter are as follows:

α = 1075 rpm clockwise (+)

β = 650 rpm counterclockwise (-)

Find: The rotational rate and direction of the receiver shaft (γ).

Solution: $\gamma = \alpha - \beta$ (Equation 1)

$= (1075 \text{ rpm}) - (-650 \text{ rpm})$

$= 1725 \text{ rpm}$

γ = 1725 rpm clockwise

Figure 20 shows the same components connected to produce angular addition instead of angular subtraction. In this case, the output angle is given by Equation 2.

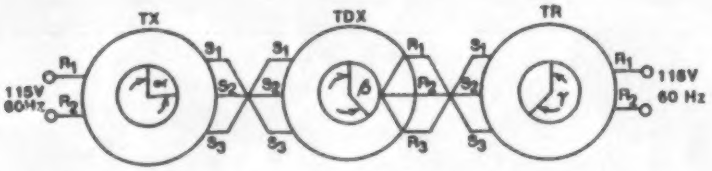


Figure 20. Circuit for Addition of Shaft Angles.

$$\gamma = \alpha + \beta \qquad \text{Equation 2}$$

This equation leads to the data in Table 2.

TABLE 2. INPUT AND OUTPUT ANGLES OF A DIFFERENTIAL SYNCHRO SYSTEM CONNECTED FOR ANGULAR ADDITION (Angles in Degrees).

Input Angles		Output Angle
α (TX)	β (TDX)	γ (TR)
45	45	90
45	0	45
0	45	45
45	-45	0
-45	45	0

Differential synchro receivers (motors) are used in the same circuits as those in Figures 19 and 20. A differential receiver accepts input signals from two synchro transmitters. The same equations apply, except that α and γ are input angles and β is the output angle. This is illustrated in Example B.

EXAMPLE B: DIFFERENTIAL SYNCHRO RECEIVER SPEED.

Given: Two synchro transmitters and a differential synchro receiver are connected as in Figure 20. The input rotational rates of the transmitter shafts are as follows:

α = 200 rpm clockwise (+)
β = 350 rpm counterclockwise (-)

Find: The rotational rate of the output shaft of the differential receiver (β).

Solution: $\gamma = \alpha + \beta$ (Equation 2)
$\beta = \gamma - \alpha$
$= -350$ rpm $-$ 200 rpm
$= -550$ rpm
β = 550 rpm counterclockwise (-)

THE SYNCHRO CONTROL TRANSFORMER

A synchro control transformer is a device used to produce an error voltage that is used by an external circuit to operate angular positioning motors. Schematically, a synchro control transformer looks exactly like a synchro transmitter or receiver, and its construction is also similar.

Figure 21 shows a synchro control transformer in an angular control circuit. The rotor of the control transformer is connected to the mechanical

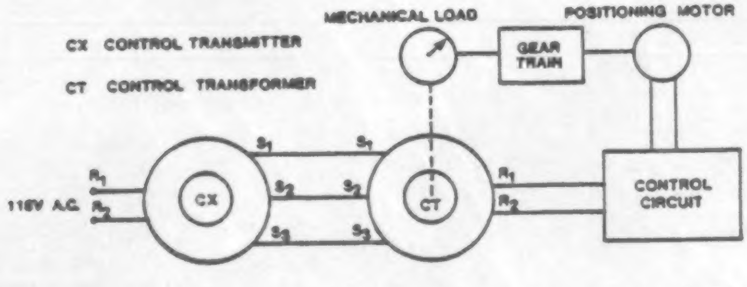

MECHANICAL LOAD
POSITIONING MOTOR
CX CONTROL TRANSMITTER
CT CONTROL TRANSFORMER
GEAR TRAIN
S_1
S_1
R_1
R_1
115V A.C.
R_2
CX
S_2
S_2
CT
R_2
CONTROL CIRCUIT
S_3
S_3

Figure 21. Synchro Control Transformer in a Control Circuit.

load. The angular position of the load is controlled by the angular position of the control transmitter (CX).

If the rotors of the two synchro mechanisms are in the positions shown in Figure 22, the output error voltage is zero and the control circuit supplies no voltage to the positioning motor. If the transmitter rotor is rotated through some angle, an error voltage is produced on the output terminals of the control transformer. The control circuit senses this voltage and turns on the positioning motor to rotate the mechanical load. The direction of the turning motor is determined by the polarity of the error signal. Since the rotor of the control transformer is connected to the load, it rotates also. When the control transformer rotor is once again perpendicular to the transmitter rotor, the error voltage is zero, and the control circuit turns off the positioning motor.

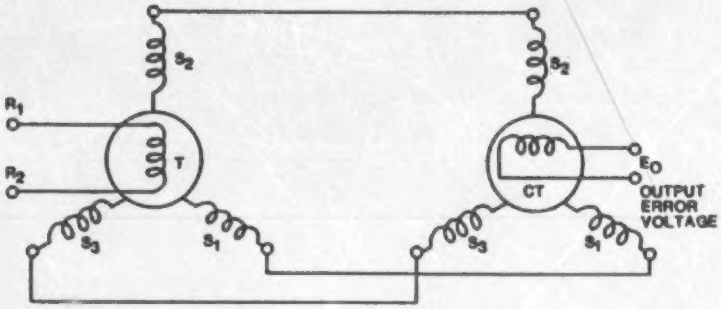


Figure 22. Transmitter-Control Transformer Pair.

CLASSIFICATION OF SYNCHROMECHANISMS

Synchromechanisms are classified according to whether they have torque or control capabilities. A torque synchro is used to deliver a torque to a mechanical load. A control synchro will transmit control signals only; it can drive an indicator but not a load. Synchros are classified according to the following letter codes:

- CX – control transmitter
- TX – torque transmitter
- TR – torque receiver
- CT – control transformer
- CDX – control differential transmitter

- TDX — torque differential transmitter
- TDR — torque differential receiver

Synchros built to military specifications have additional information indicating size and frequency. For example, 23TX4 indicates a torque transmitter that is 23 inches in diameter and operates on 400 Hz. Synchros usually operate on 400 Hz or 60 Hz. A final digit of 6 indicates a 60 Hz synchro.

APPLICATIONS OF SYNCHROMECHANISMS

Synchro transmitter-receiver pairs and differential synchro systems are widely used for the synchronization and control of rotating shafts in industrial processes. Areas of application include paper mills, textile mills, steel mills, and many other situations in which shafts must rotate at synchronous or differential speed but are physically too far apart for mechanical linkages to be practical.

The synchro control transformer is widely used for angular positioning of antennas, telescopes, gun mounts, and other pointing devices.

EXERCISES

1. Two shafts rotate in a clockwise direction with rates of 600 rpm and 900 rpm. A third shaft is to rotate clockwise with a rate of 300 rpm. Draw a synchro circuit using a TX, a TDX, and a TR that will accomplish this. Indicate the rotational rate and direction of each shaft on the diagram.
2. Draw a schematic diagram of a synchro transmitter-receiver pair in which a clockwise rotation of the transmitter rotor produces a counterclockwise rotation of the receiver rotor.
3. Two shafts rotate in a clockwise direction with rates of α = 600 rpm and β = 900 rpm. A third shaft is to be driven at 300 rpm in the counterclockwise direction. Draw a synchro circuit to accomplish this, using a TX, a TDX, and a TR. Indicate the rotational rate and direction of each shaft on the diagram.
4. What happens in a control circuit employing a synchro control transformer if the rotor connections of the transformer are reversed?

5. Explain why the receiver rotor shaft will lag behind the transmitter rotor shaft by as much as 3° when a synchro transmitter-receiver pair is used for torque transmission.
6. Which of the seven types of synchromechanisms is never connected directly to an a.c. power line?

LABORATORY MATERIALS

Variable transformer, 0-130 V a.c.
Synchro transmitter type 23TX6 or equivalent with mount
Synchro receiver type 23TR6 or equivalent with mount
Synchro differential transmitter type 23CDX6 or equivalent with mount
VOM
Three 360° disk dials to fit synchro rotor shafts
Connecting wires

LABORATORY PROCEDURES

1. Construct the circuit shown in Figure 23, using the synchro transmitter (23TX6).

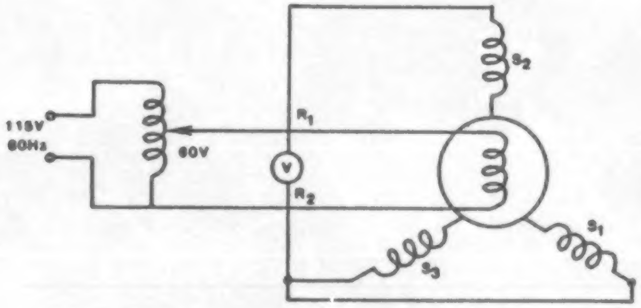


Figure 23. Electrical Zero Experimental Circuit by Jumper Method.

2. Set the autotransformer voltage to 60 V. The synchro rotor will move to the electrical zero position. Set the shaft indicator dial to 0°.

3. Repeat Steps 1 and 2, using the synchro receiver (23TR6). Both dials should remain set to read 0° at the electrical zero position throughout the laboratory.
4. Using the circuit shown in Figure 24, check the electrical zero of both synchros.

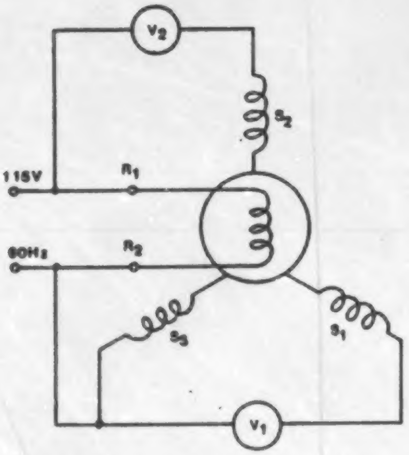


Figure 24. Electrical Zero Experimental Circuit by Voltmeter Method.

5. Construct the circuit shown in Figure 25. Set the synchro transmitter for 0°. Record the angular positions of the output shaft in Section 1 of the Data Table (direct stator connection).

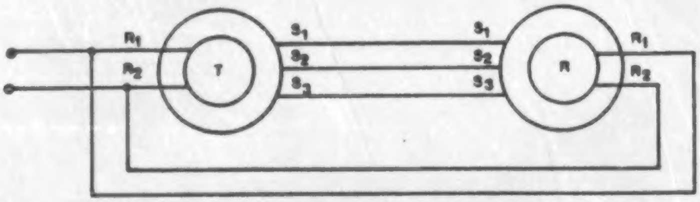


Figure 25. First Experimental Circuit.

6. Rotate the input shaft to the other angles indicated in the Data Table and record the angle of the output shaft for each.
7. Disconnect the power from the experimental circuit and rewire it as shown in Figure 26.

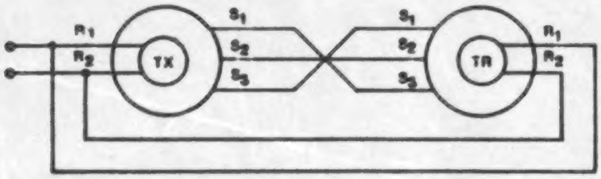

R1
R2
TX
S1
S2
S3
S1
S2
S3
TR
R1
R2

Figure 26. Second Experimental Circuit.

8. Repeat Step 6 for this circuit, recording the output shaft angle in the "reversed stator connection" column of the Data Table.
9. Construct the circuit shown in Figure 27.

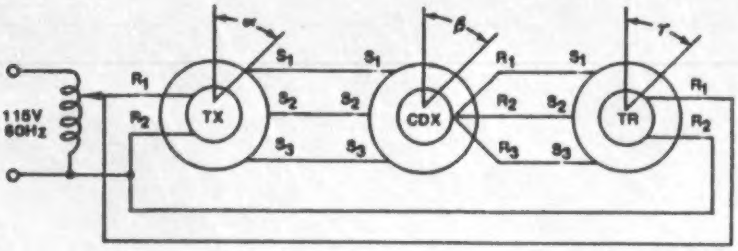

α
β
γ
115V
60HZ
R1
R2
TX
S1
S2
S3
S1
S2
S3
CDX
R1
R2
R3
S1
S2
S3
TR
R1
R2

Figure 27. Third Experimental Circuit.

10. Set the transmitter for electrical zero (0°). The electrical zero of the differential transmitter (CDX) is its rotor position that produces a receiver (TR) angle of 0° when the transmitter (TX) is at 0°. Set CDX to the electrical zero and set its dial indicator to 0°.
11. Set the input shafts to the angular positions indicated in Section 2 of the Data Table and record the output angle for each combination.
12. Disconnect the power from the experimental circuit and rewire it as shown in Figure 28.

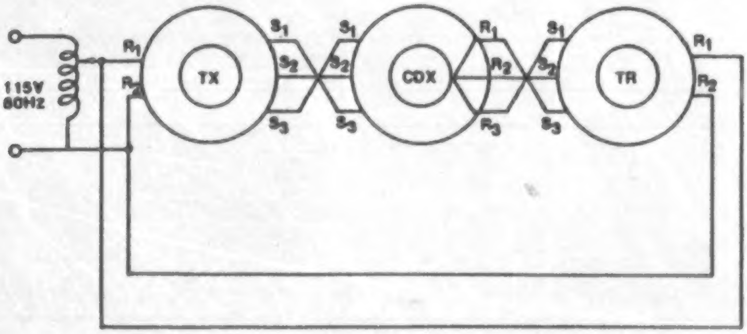

115V
60HZ
R1
R2
TX
S1
S2
S3
S1
S2
S3
CDX
R1
R2
R3
S1
S2
S3
TR
R1
R2

Figure 28. Fourth Experimental Circuit.

13. Repeat Step 11, recording data in Section 3 of the Data Table.
14. Refer to Exercise 3. Construct the circuit required in this exercise and record data on this circuit in Section 4 of the Data Table.
15. Evaluate the data in Section 4 to determine if the schematic drawn in Exercise 3 produces the desired results. Explain all findings.

DATA TABLE

DATA TABLE.

SECTION 1. SYNCHRO TRANSMITTER-RECEIVER PAIR (First and Second Experimental Circuits.		
Input Shaft (TX) Angle In Degrees	Output Shaft Angle (TR) In Degrees	
	Direct Stator Connection	Reversed Stator Connection
0		
45		
90		
135		
180		
225		
270		
315		
360		

SECTION 2. ANGULAR SUBTRACTION WITH DIFFERENTIAL SYNCHRO (Third Experimental Circuit).		
Input Angles in Degrees		Output Angle (γ) In Degrees
α	β	
0	45	
45	45	
45	-45	
-45	45	
90	180	
-90	180	
90	-180	
-90	-180	

Data Table. Continued.

SECTION 3. ANGULAR ADDITION WITH DIFFERENTIAL SYNCHRO
(Fourth Experimental Circuit).

Input Angles In Degrees		Output Angle (γ) In Degrees
α	β	
0	45	
45	45	
45	-45	
-45	45	
90	180	
-90	180	
90	-180	
-90	-180	

SECTION 4. FIFTH EXPERIMENTAL CIRCUIT
(See Exercise 3).

Input Angles In Degrees		Output Angle (γ) In Degrees
α	β	
0	45	
45	45	
45	-45	
-45	45	
90	180	
-90	180	
90	-180	
-90	-180	

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